Degradation of Forested Land: "Forest Soils at Risk"

Proceedings of the 10th B.C. Soil Science Workshop February, 1986

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FOREWORD

Future forest growth depends on maintaining forest soil productivity. Minor forest soil disturbance may be beneficial in establishing a new forest, but excessive disturbance may degrade the soil and reduce future timber yields.

Soil degradation has been a topic of concern and research in the U.S. since the late 1940's; in British Columbia, similar recognition did not occur until the early 1970's. In the Pacific Northwest of the United States, considerable research has been undertaken, especially in the last 10 years, to quantify the effects of forest harvesting practices on site productivity. This research has shown some alarming trends. The decrease in stand growth as a result of forest soil disturbance has been estimated at as much as 15% in some cases, and the effects can last up to 50 years, or longer.

Meanwhile, forest harvesting in British Columbia has moved to progressively more sensitive sites. These sites tend to be steeper and have shallower, drier soils than the more fertile bottomlands frequently harvested in the past. In B.C., the industry has often been slow to recognize the need for lower impact harvesting systems and for more rigorous planning and ground control systems on these more sensitive sites. The net result is that the steeper, generally more sensitive sites are often heavily impacted by forest harvesting.

The B.C. Ministry of Forests and Lands is charged with the legislative responsibility to manage forest resources so as to maximize long-term socio-economic benefits. This cannot be done unless all the costs and benefits of our forest management regimes are known — and this means understanding the nature, extent, and productivity effects of site disturbance from forest management operations. An inaccurate or incomplete understanding of the effects of forest site degradation on productivity, coupled with a reluctance to include realistic productivity reduction estimates in TSA analyses, could lead to serious long-term economic consequences for the province of British Columbia.

In February 1986, a forest soil degradation workshop was held at the University of British Columbia. The objectives of this workshop were to bring together people with the most up-to-date research knowledge and experience about forest soil degradation, and provide a forum for discussion with operational foresters and resource managers. In this regard, the workshop attracted some of the foremost researchers in the field, and an impressive audience comprised of foresters, engineers, soil scientists, ecologists, researchers, university students, and others. As a result, awareness of forest site degradation has increased significantly in British Columbia.

Information presented at the workshop effectively defined what is now known (and not known) about forest site degradation. Much of this information originates from the United States. It is clear that the U.S. Forest Service is well on its way to answering many important forest site degradation questions for their own conditions and socio-economic circumstances. We in British Columbia can benefit from that work but, as was emphasized at the workshop, our climate, soils, vegetation and operating practices are different, so that it is imperative to quantify causes and effects for our own conditions and, in the interim, manage prudently and conservatively. There is clearly much work to be done, both in terms of needed research and with respect to improving public and professional awareness about the issues.

The publication of these proceedings is the culmination of the workshop. Because of the comprehensive program and the stature of the participants who presented papers and posters at the workshop, this document should stand as a landmark reference for British Columbia researchers for many years to come.

G.W. Still, Chairman
Organizing Committee

J. Cuthbert,
Chief Forester
British Columbia Ministry of
Forests and Lands

ACKNOWLEDGEMENTS

In principle, organizing and presenting a workshop and publishing the proceedings should be straightforward and relatively simple. Impose upon this process several intangibles, such as an important and controversial workshop theme, an international forestry community, a high level of commitment in the forestry profession today, a great diversity of thought and opinions, heavy workloads, missed deadlines, lost manuscripts or pieces thereof, and it soon becomes apparent that the contributions of several people and organizations, much patience and time, and good coordination are required.

We must acknowledge first the support and interest from the Ministry of Forests and Lands, particularly from John Cuthbert, Chief Forester, and many staff in timber management, engineering, silviculture and research in the headquarters, regional and district offices. Ted Baker of the Research Branch was responsible for suggesting and promoting the theme of forest soil degradation within the Land Resource Science Lead Committee and for commiting direct MoFL support. We must acknowledge also our other sponsors: the Land Resource Science Lead Committee for allowing us to use the annual B.C. Soil Science Workshop as our vehicle of presentation; and the B.C. Chapter of the Soil Conservation Society of America and its commitment to soil conservation throughout the natural resource sectors of this province. The Department of Soil Science at The University of British Columbia, particularly through the efforts of Les Lavkulich and Tim Ballard, again was a most gracious and supportive host. The initial ideas for workshop content were discussed in meetings of the Soil Degradation and Rehabilitation Committee, an interagency group of professionals dedicated to responsible soils management. The workshop organizing committee, comprised of Gerry Still, Tim Ballard, Dick Smith and Dan Lousier, had the responsibility of establishing the program and the format, selecting the invited speakers and session chairman, and organizing on-campus facilities and logistics. Our efforts were rewarded by the excellent presentations by the speakers and the spontaneous participation of the audience.

Logistical support prior to and during the workshop was provided by Bernie von Spindler, Peter Synadinos, Lexi Clague, Heather McIntyre, Mike Curran, Tom Braumandl and Steve Thompson. Because of their unselfish efforts, the workshop was 'glitch-free' for the full two days. After the fun and excitement of the workshop, the process of collating, editing and publishing the proceedings has been somewhat arduous and lengthy. Special acknowledgements must go to the Research Branch word-processing staff, Louise Gronmyr, Jean Stringer and Edna Lomas, for their patience, aptitude and good cheer. The editorial process was immeasurably assisted by Georgina Montgomery. Any mistakes or omissions remaining in the manuscript are the responsibility of the proceedings editors.

Finally, our heartfelt thanks and appreciation to the main players in the workshop and the proceedings: the session chairmen who performed admirably all that we asked of them; the manuscript reviewers for their judgment, candor, constructive inputs, tolerance and for the promptness of their reviews; and the authors for the quality of their papers, their positive and enthusiastic response to the reviewers' contributions, and their patience with the editorial process and the editors.

We have striven to produce a proceedings of high technical content and of high quality presentation. Each paper has been reviewed by at least two specialists in the same field and the proceedings as a whole have been edited four times. This has taken some time but we feel that the subject matter has been covered in a broad, balanced and direct manner so as to be useful to land managers, land use planners, researchers and the general public when dealing with and understanding land resource conflicts or soil conservation. We are grateful for the opportunity of organizing and participating in the workshop and of compiling the proceedings. We believe the information and message presented in these proceedings are clear: to ensure the longevity of healthy, productive forests, we must understand our soils resource and manage it with care.

G.W. Still, R.P.F., P. Ag.
Chairman, Organizing Committee

Dan Lousier

J.D. Lousier, P. Ag.
Editor

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OPENING REMARKS AND WELCOME

L.M. Lavkulich
Chairman
B.C. Land Resource Science Lead Committee

As chairman of the British Columbia Land Resource Science Lead Committee, I wish to greet you with a warm welcome to this Tenth British Columbia Soil Science Workshop on the topic of Degradation of Forested Land: Forest Soils at Risk. There has been much publicity about the degradation that is taking place to the nation's soil resource. Most of the attention has been focussed on agricultural land. I think it appropriate that British Columbia hold, as far as I am aware, the first Soil Science workshop in Canada addressing forest soil degradation.

The forest industry in this province is plagued with problems of which you are aware. British Columbia does not have abundant prime forest land. Much of the prime land for forestry is being pressured for other uses, such as agriculture, urban development, and transportation corridors. What forest land we have needs to be nurtured to maintain a healthy forest industry.

The program for the next two days is full and interesting, addressing such things as causes and effects of soil degradation, effects of degradation on productivity, how it may be predicted or controlled, methods of rehabilitation once degradation has occurred, the economics of land degradation, and finally, research needs.

I am pleased that the Land Resource Science Lead Committee, along with the British Columbia Ministry of Forests and Lands and the British Columbia Chapter of the Soil Conservation Society of America, have sponsored such an important workshop. On behalf of all of you I want to thank, in advance, all the speakers for preparing their presentations and the chairpersons for keeping things in line. I know this is going to be a successful workshop. Please get involved in the discussions, not only during the formal sessions, but also at breaks, lunch, and in the evening. Please observe the poster sessions as they all have a message to deliver.

I want to thank the British Columbia Ministry of Forests and Lands for taking on the task of publishing the proceedings of this workshop. Also, I wish to thank Gerry Still, Chairman of the Organizing Committee, Dan Lousier and Tim Ballard, Mike Curran, Bernie von Spindler, Peter Synadinos, Lexi Clague, and Heather McIntyre. Their dedication is much appreciated. To all familiar faces, and to the new faces, I welcome you to the workshop and hope everyone has an enjoyable and rewarding time.

SESSION 1

Forest Soil Degradation: Causes/Effects

1-1 Timber Harvesting
1-2 Roads
1-3 Forest Site Preparation

Session Chairman:
R. Green
Research Pedologist
Vancouver Forest Region
Burnaby

SESSION 1-1 TIMBER HARVESTING

CAUSES AND EFFECTS OF SOIL DEGRADATION DUE TO TIMBER HARVESTING

H.A. Froehlich
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Oregon State University, Corvallis, OR

ABSTRACT

Research from the past few decades has documented the various changes that timber harvesting can produce in the surface layers of forest soil. Most of these changes are found to reduce soil productivity. Soil compaction, displacement and puddling are the most commonly observed negative impacts produced during logging or site preparation. Reductions of tree growth due to these impacts have been reported from many parts of the world. Growth reductions of from 5 to 15% have been observed in young-growth stands, compared to sites without a measurable harvesting impact.

The simple need for access to harvest any given area economically will typically require that from 5 to 10% of the land be dedicated to haul roads. If the remainder of the land is to continue to be productive, it must be treated as a limited resource and the impacts kept to a realistic minimum. Setting goals or standards for acceptable levels of impact is a reasonable first step, but careful planning and responsible supervision will be needed to achieve them. Corrective steps can be taken to alleviate some adverse conditions and these should be planned and directed along with other site preparation measures.

1 INTRODUCTION

Soil degradation is taken here to be any change in a soil's physical and chemical properties that reduces the productivity of a site. In this morning's session we will concentrate on the physical impacts on soils associated with tractive and cable logging, site preparation, and roads. Several decades of research have documented the changes in soil properties produced by forest management activities in virtually every forested area in the world. It is obvious that we cannot realistically expect to capture the productivity of a large forested area without taking some of the land more or less permanently out of production. We will also likely reduce the potential of some of the remaining land to grow wood fiber.

The decision we face is how to keep any permanent and temporary soil impacts to an acceptably low level. This requires a long-term view of the land as a perpetual source of wood products and other resources as well. Overly restrictive limits on acceptable harvesting practices can have the effect of making an important resource economically unavailable. Thus, extreme restrictions can also have a negative impact on society. Managing forest land to strike the appropriate balance will be a continual challenge.

2 ROAD SYSTEMS

Adequate road systems are the key to managing large tracts of forest land effectively. Developing nations, for example, may be rich in resources yet suffer from lack of access to these resources and lack of an infrastructure capable of moving the resource to present markets. Knowing that the road system and some landings will remove considerable acreage from the land base does not always keep us from building excessive numbers of roads, sometimes of excessive width, and from creating oversized landings.

Most forest managers can tell you exactly how many hectares are under their ownership or management. Relatively few can tell you how many hectares of land are dedicated to permanent roads or landings.

Some of the published reports of the amount of land dedicated to the system of truck roads are given in Table 1. Some of these reports do not include landings, and none of them includes major skid trails. The wide variation reported by Dissmeyer (1976) is the result of some operations driving their trucks to landings not served by a developed road system. The undeveloped haul tracks are severely compacted but are not inventoried as part of the road system. The key question here is: What is the minimum acreage we can give to roadways and still have reasonable access? A glance at aerial photographs of forest often shows examples of unnecessary roads and extensive landings.

The quality of road design, construction and maintenance determines in large measure what soil losses, if any, are added to the initial displacement required by the development of the road system. Mass soil movements from road cuts and fills, as well as surface erosion, may add to the area initially affected. Of course, this secondary soil loss may have even more important consequences downslope or downstream.

TABLE 1. Land utilized for roadways by various logging methods

Logging Method and Region	Data Source	Area Given to Roads (%)
Long-reach skyline Pacific Northwest	Binkley 1965	2
Highlead Cascades Oregon	Swanson and Dyrness 1975	3-3.5
Highlead Cascades Oregon	Silen 1957	7.3
Highlead Idaho	Megahan and Kidd 1972	10
Jammer Idaho	Megahan and Kidd 1972	18-24
Jammer Central Appalachia	Kochenderfer 1977	7.8
Small crawler tractor Idaho	Haupt 1960	10
Large crawler tractor Idaho	Haupt 1960	4
Rubber-tired skidder Central Appalachia	Kochenderfer 1977	10.3
Rubber-tired skidder Southeast	Dissmeyer 1976	1.2-17.1

3 SOIL DISPLACEMENT

Displacing soil to a depth and extent such that the site is not likely to be used by tree roots would seem to be a growth-reducing impact. Few studies have carefully evaluated the growth response on a large site with a high density of excavated skid trails. I have long held the opinion that if one had to excavate a trail to stay on the slope, the site was too steep to harvest with tractive machines.

Wellburn (1975) noted that skid trails must be excavated when crawler tractors are being used to skid on slopes in excess of 30%. He suggested that, on slopes over 70%, the area in skid trails becomes excessive. Wellburn also stated that tractors can operate successfully on frozen snow without excessive soil disturbance on slopes of up to 100%.

Smith and Wass (1976), studying soil disturbance in the Nelson Forest District of British Columbia, reported that an average of 31.5% of the clearcut area logged during summer was covered by skidroads, cut banks and sidecast material. The proportion of area covered by the same types of excavations in winter-logged areas was 17.8%. Hill slopes between 29.9 and 39.9% were found to have 47.1% of the area disturbed. Slopes ranging from 40 to 81% had an average of 30% of the area disturbed. Soil excavated to a depth greater than 25 cm was considered to be a degraded site.

It is hoped that earlier seedling establishment and freedom from competing vegetation could improve the early growth of seedlings in some areas where sidecast topsoil provides deeper, richer soil. Smith and Wass (1979) observed the establishment and growth of conifer seedlings which were generally less than 100 cm tall. They reported on the enhancement of height growth of seedlings in some disturbed locations which they believed would offset the negative growth rate observed on portions of the skid trails on some soil types. On other soil types and aspects, the effect on the site was a measurable reduction in productivity In the normal forest floor, the roots are concentrated in the surface layers of soil and humus and thoroughly occupy the site. In the areas of excavation in excess of 25 cm, however, normal root extension is likely to be limited by the excavated and compacted skid trails. The long-term growth pattern for conifer trees on these sites still needs to be determined.

I could find no information on costs or practical methods of restoring excavated trails. If the residual soil in the excavated trail is deep enough there might be some gain in productivity by tilling to provide an improved rooting medium. In shallow, stony soils it is unlikely that loosening the lower quality subsoils would markedly improve seedling growth.

4 SOIL COMPACTION AND PUDDLING

Just as roads are generally assumed to be an unavoidable consequence of forest management, soil impacts from any logging operation are also at times assumed to be unavoidable, inconsequential, or of short duration. We now know that none of these views is entirely true. Research has shown that soil productivity can be seriously affected and the impacts are commonly found to be long-lasting. Furthermore, there are ways to keep the adverse impacts to a much lower level than we formerly accepted.

Many early studies (to 1960) concentrated on the area disturbed rather than on the physical changes that took place at the disturbed locations. Table 2 summarizes some of these observations. The authors did not all use the same definition of 'shallow" or "deep" disturbance. Generally shallow disturbance was the exposure of mineral soil to a depth of 5-25 cm. Deep disturbance was exposure of mineral soil to subsoil or a depth greater than 5-25 cm. Shallow disturbance not accompanied by compaction or puddling was sometimes considered to be beneficial. The contrast between cable and tractive systems in the deep disturbance category is very apparent.

Later observations began to reveal that, even under shallow disturbance in tractor-logged areas, significant changes in soil properties resulted. Observers have also indicated that mechanical site preparation can have negative impacts on the underlying soils. The catalog of effects of soil compaction and puddling, which may be produced by heavy equipment during harvesting and post-harvesting activities, includes:

1. increase in bulk density;
2. decrease in total pore space;
3. decrease in non-capillary pore space;
4. increase in capillary pore space at low compactive effort;
5. decrease in capillary pore space at high compactive effort;
6. decrease in infiltration rate;
7. decrease in permeability;
8. decrease in effective pore diameter;
9. increase in available water-holding capacity followed by decreasing water-holding capacity at higher compactive effort;
10. increase in soil strength at comparable soil moisture content as measured by shear vane or cone penetrometer; and
11. change in soil structure from granular to platey to massive as compactive effort increases.

TABLE 2. Degree of soil disturbance by various logging methods

Logging Method and Region	Data Source	Area Disturbed (%)		
		Shallow	Deep	Total
Skyline crane, clearcut Washington	Wooldridge 1960	2.2	3.2	5.4
Skyline crane, clearcut Oregon	Dyrness 1972	–	5	5
Skyline, thinning Oregon	Aulerich *et al.* 1974	4	–	4
Highlead, clearcut Oregon	Dyrness 1965	21	10	31
Balloon, clearcut Oregon	Dyrness 1965	16	4.3	20.3
Tractor, clearcut Oregon	Dyrness 1965	26	36	62
Tractor, thinning Oregon	Aulerich *et al.* 1974	24	–	24
Tractor, partial cut Washington	Wooldridge 1960	6.3	16	22.3
Tractor, clearcut Washington	Steinbrenner and Gessel 1955	–	26	26
Tractor, clearcut Oregon, Washington	Garrison and Rummell 1951	5.9	15	20.9
Tractor, partial cut California	Munns 1947	–	–	25-40
Tractor, partial cut Idaho	Haupt 1960	–	–	3-18
Tractor, partial cut California	Fowells and Schubert 1951	–	–	22
Horse logging, partial cut, Oregon and Washington	Garrison and Rummell 1951	9.5	2.3	11.8

Bulk density is the most common variable — often the only variable — used to monitor soil impacts. Table 3 summarizes the results from several studies and it is apparent that increases in soil density serve as a reasonable index to changes in pore space and permeability.

Soil strength as measured by various cone penetrometers has been included as a variable modified by soil compaction (Cochran 1971; Sands and Bowen 1978; Froehlich and McNabb 1984). Resistance to penetration appears to be a more sensitive indicator of adverse soil impacts than bulk density. Tree root extension has been shown to be markedly reduced with increasing resistance to cone penetration (Zisa *et al.* 1980).

All types of tractive logging systems share two characteristics: 1) enough ground pressure to assure traction, even on slopes up to about 45%; and 2) a level of vibration which increases the effectiveness of the pressure to change soil properties. The principle of soil compaction utilizing these two elements is well understood by engineers. Building a strong subgrade is effectively improved by using a vibratory roller at some optimum soil moisture level. Fortunately, the effect of conventional logging equipment on soil is not as extreme.

TABLE 3. Some changes in physical soil properties produced by compaction of forest soils (expressed as percent change from undisturbed soil)

Source	Bulk Density	Total Porespace	Noncapillary Porespace	Permeability
Campbell *et al.* 1973	+19	-11	-28	–
	+13	-16	-64	–
	+37	-20	-72	–
Dickerson 1976	+10	–	-38	-65
	+20	–	-68	-90
Dyrness 1965	+62	-18	–	–
Froehlich *et al.* 1981	+12	–	43	-80
Hatchell *et al.* 1970	+23	–	-29	–
	+44	–	-40	–
	+34	-16	-50	–
Moehring and Rawls 1970	+13	-11	-49	–
Steinbrenner and Gessel 1955	+2.4	–	-11	-35
	+35	–	-53	-92

There are differences both in ground pressure and in the amount or intensity of vibration transmitted to the soil by various types of equipment. Table 4 shows the variation in ground pressure among machines. Notice the large difference between static ground pressure and the computed dynamic loading when the machine is pulling a turn of logs. The differences between the suspension system of the machines, as well as between tires and tracks on transmitting vibration to the soil, are probably causative factors in the somewhat higher soil densities under skid trails produced by crawler tractors (Froehlich *et al.* 1980). Some recent results of observations on skidders equipped with wide tires indicated that under some conditions they will produce significantly less soil impact than tires of conventional width (Rollerson and Kennedy 1984). Miles and Froehlich (1984) measured soil density changes with number of trips on the McDonald Forest near Corvallis, Oregon. Four sections of skid trails were designated to receive 2, 12, 20 and 40 round trips by a JD 640 skidder. This skidder was equipped with Goodyear Terra-grip tires which are 185 cm in diameter and 112 cm wide. The tires were inflated to 200 kPa. Measurements made to a depth of 30 cm showed that the 2, 12, 20 and 40 trips produced 9.6, 10.0, 12.8 and 27.5% increases in soil density, respectively, over a 30 cm depth. Clearly more work is needed to define the conditions under which the wide tires are effective in minimizing soil compaction.

The effect of various other types of logging equipment on forest soils has received very little study. The maximum dynamic pressure exerted by feller-bunchers and whole-tree harvesters could be calculated using the equations by Lysne and Burditt (1983). Preliminary field observation of soil compaction produced by a feller-buncher, followed by grapple skidding, showed a greater than 25% increase in soil density on 40% of the cutting unit.[1] The increase in mechanization has greatly increased the potential for reducing site quality. More studies are needed to learn what soil changes might be expected from many other harvesting machines now in common use, as well as for new types of equipment being introduced to the logging industry.

---

[1] D. Murdough, personal communication, 1984, Soil Scientist, USDA Forest Service, Willamette National Forest.

TABLE 4. Logging vehicle ground-pressures on level ground

	Pressure, KPa		
	Static	Dynamic, with Log Turn	
		Leading Track/Tire	Trailing Track/Tire
Caterpillar DGD, 17 687 kg w/ 6802 kg load	64	40	110
FMC 210CA 13 152 kg w/ 6802 kg load	41	45	60
John Deere 640 9070 kg w/ 3628 kg load	66	70	85

After Lysne and Burditt (1983)

5 MINIMIZING SOIL IMPACTS

We need to continue to search for ways to reduce the ground pressure and vibration of logging machines. Even if no breakthrough in equipment design were to occur, we could markedly reduce the amount of land impacted by machines. At least three studies have shown that designating skid trails in advance of harvesting can limit the area in trails to as low as 5-10%. When the area of trails was held to about 5%, skidding costs increased by about 30%. At a trail spacing of about 45 m, or about 7% of the area in skid trails, little or no increase in skidding costs were encountered (Froehlich *et al.* 1981). Olsen and Siefert (1984) found that with designated trails covering 9% of the area, changes in skidding costs ranged from -2 to +1%. These three studies compared skidding costs on designated trails with conventional skidding or "loggers choice" using hand-felling and choker-skidding.

Some European countries are experimenting with radio-controlled winches and dual winches on skidding machines to improve the efficiency of logging to well-spaced skid trails. These show promise in helping to keep the area in skid trails to a very low amount without large increases in cost.

6 RESTORATION OF COMPACTED SOIL

Several studies have shown that natural forces are present which tend to loosen compacted and puddled soils, but these require considerable time to achieve much loosening (Thorud and Frissel 1976; Wert and Thomas 1981; Froehlich *et al.* 1985). A generalization was made a few decades ago that it would take about the length of a harvest rotation for skid trails to recover to normal densities. This assessment appears to be realistic, even for coarse-textured soils.

A recent study on how to speed the recovery process showed that major improvement in soil tilth can be accomplished at a relatively modest cost (Andrus and Froehlich 1983). During this study a number of site improvement projects were observed. We found that too often, neither contractor nor contract supervisor knew what was intended to be accomplished. On some sites, as little as 15% of the compacted soil was actually fractured by the ripping, plowing or disking operations.

Better assessment of the type and extent of soil problems is needed to write an appropriate prescription for treatment. Depth of tillage, degree of fracturing, timing, and exact areas to be tilled all need to be defined in the contract and understood by the contract supervisor.

The gains in seedling growth observed in several studies were quite variable. The gain depended on many factors not always identified in the research paper. The quality of tillage was no doubt a major factor. Also, some of the sites were not as seriously degraded prior to treatment and the response to loosening is likely to be relatively low compared to that expected where compaction was severe. As with most facets of the problem of soil degradation, more study is needed to define the actual gain in growth from soil tillage.

7 GROWTH REDUCTIONS ON DEGRADED SITES

Soil compaction, deep soil displacement and puddling all appear to be associated with reduced seedling and tree growth. Decreases in seedling height growth of 10-50% have been reported. There is a strong correlation between the degree of compaction on a wide variety of soils and increasing reduction in height growth. More recently it has been demonstrated that there is a considerably higher percent reduction in stem volume than in tree height (Froehlich *et al.* 1986). Compaction around residual trees following thinning has also been shown to reduce basal area growth. Few studies have measured the combined effects of soil impacts on stand volume. Estimates of losses in productivity on a stand basis, excluding roads and landings, range from 5 to 15% in stands ranging from 17 to 30 years old (Wert and Thomas 1981; Helms 1983; Froehlich and McNabb 1984).

8 CONCLUSION

Each of the potential causes of reduced wood production on a piece of forest land impacted by roads, landings, yarding or skidding, and site preparation, when taken individually, may seem insignificant. Yet we should consider that, when these factors are combined, the total may be higher than we formerly thought was possible. Perhaps taking an inventory of the area in roads, landings and skid tails and the productivity on these sites on a number of tracts would reveal the extent that past activities have reduced the growth potential of the tract. I believe we need to establish a goal to keep all of the possible growth-reducing impacts to the lowest possible economic level.

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SESSION 1-1 TIMBER HARVESTING

ENVIRONMENTAL IMPACT OF GROUND HARVESTING SYSTEMS ON STEEP SLOPES IN THE VERNON FOREST DISTRICT

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ABSTRACT

Several areas on steep slopes in the Vernon Forest District were examined to assess the environmental impact of conventional ground harvesting systems. The results indicated excessive excavation on many sites, often leading to slope failure and surface erosion. Regeneration on the compacted surfaces was usually growing poorly or was nonexistent. This was attributed to the loss of surface litter and topsoil, as well as to the reduction in soil macropore space. Many of the skidroads and landings were intercepting surface and/or ground water flow, resulting in surface erosion and channelling of water away from the downslope vegetation.

A reconnaissance survey of six areas indicated disturbance levels ranging from 17 to 61%. The average cut slope height on skidroads ranged from 0.9 to 2.9 m. Using small crawler tractors to construct skidroads on a snowpack produced the least disturbance and the smallest skidroads.

It was concluded that many of the ground harvesting methods in use were causing excessive site degradation and productivity losses. Guidelines for skidroads and landings were subsequently drafted, attempting to minimize site degradation through modification of harvesting systems or the use of alternative yarding equipment.

1 INTRODUCTION

Some of the more productive sites for the growth of timber in the Vernon Forest district are located on the steep slopes of the mountains in the eastern portion of the district. This area is dominated by the Interior Cedar-Hemlock (ICH) and Engelmann Spruce-Subalpine Fir (ESSF) Biogeoclimatic Zones. With some exceptions, the soils of these areas are mostly morainal or colluvial and overlie bedrock that is predominantly granitoid gneiss in the north and granodiorite in the south (Jones 1960). This parent material is generally local in origin and consequently has a poor to very poor nutritional status (Walmsley *et al.* 1980). Most of the nutrient capital of the site is concentrated in the organic horizons and the upper few centimeters of mineral soil (R. Kowall, pers. comm.). It has taken hundreds of years for this organic matter to accumulate and enrich the upper soil layers (J.P. Kimmins, pers. comm.). In a matter of hours, poorly planned or executed harvesting operations can displace vast amounts of this topsoil and predispose the remaining material to erosion, mass wasting, frost heaving and drying out.

The purpose of this report is to assess the impact of ground skidding systems on steep slopes in the Vernon Forest District and to make recommendations for preventing or ameliorating potential site degradation and/or negative impacts on other resource values.

2 CAUSES OF DEGRADATION TO THE SITE AND OTHER RESOURCE VALUES

2.1 Loss of Organic Matter

In specific instances, soil organic matter has been demonstrated to be the most important component of seedbeds and of rooting substrata supporting natural regeneration in the Rocky Mountains (Harvey 1982). Organic matter provides the environment and energy source for micro-organisms that contribute to decay processes, nitrogen conversions and the ectomycorrhizal activities that are particularly important to conifers. Kimmins (1987) says:

> ... in most cases the productive potential of the site is vested in a relatively thin surface layer of soil, and erosion of only the surface few centimeters of soil may be accompanied by significant reductions in plant growth.

Organic matter protects against surface erosion by decreasing the erosive power and runoff velocity. It regulates the soil moisture status by promoting water infiltration and reducing evaporation. Organic matter also moderates soil temperatures, thereby preventing frost heaving, and tends to promote soil aggregation necessary for favorable structure and porosity. Also, beneficial soil organisms require organic matter. Finally, organic matter contributes to the cation exchange capability of the soil and produces acids which promote weathering of soil minerals.

Photos 1-3 illustrate the large amounts of organic matter that have been displaced from some steep slopes in the Vernon District, ranging from Derry Creek in the far north, to Winnifred Creek in the south and Marsh Lake in the middle. On many of these exposed coarse soils, it is likely that the plant community will regress to a seral brush stage that is tolerant of nutrient-poor soils. Coniferous growth will probably be retarded for several decades until a nutrient pool accumulates in the upper soil layers and the forest floor begins to re-establish (J.P. Kimmins, pers. comm.).

2.2 Interruption of Normal Downslope Movement of Water, Soil and Plant Nutrients

Skid trails, roads and landings can affect subsurface water flow by intercepting the water at the cutslope and diverting it down ditches or roadways as surface runoff. The disrupted pattern of water flow shown in Photo 4 is still present despite having initially occurred because of logging 14 years ago.

Potential impacts are:

1. failure of cutbanks as water emerges; soil becomes saturated prior to emergence (see Photo 5). Cutbank failures usually fill in drainage ditches and produce sediment, which inevitably finds its way to stream channels (Dyrness 1967);
2. reduction of site productivity due to interruption of subsurface flow of water and nutrients to downslope vegetation;
3. decrease in stream response time and increase in flood peaks. These are caused by short-circuiting of water which previously flowed slowly through the soil (meters per day) and subsequently flows rapidly to stream channels (meters per second) (Wilford 1975);
4. less water is stored in the soil, thus reducing low flows which depend on seepage and may already be critical (Wilford 1975); and
5. increased erosive power of intercepted sub-surface flow due to a dramatic increase in velocity.

Ponding and diversion of surface flows, through the construction of trails, roads and landings, cause saturation and a resultant increase in pore water pressures. This may lead to fill failures and soil flows (see Photo 5). Furthermore, diverted surface flows may erode road surfaces, overtax ditches and culverts, cause slope failure, and disturb or destroy growing sites through soil erosion, soil and debris deposition, or an excess of moisture (Wilford 1975). Photo 6 is an example of diverted surface flow.

2.3 Soil Compaction

Steinbrenner and Gessel (1955) observed that four passes over a skidroad with an HD20 tractor reduced the soil macropore space by 50% and the infiltration rate by 80%. Measurements of bulk density in skidroads up to 25 years of age suggested little or no recovery from compacted conditions (Schwab and Watt 1981). Compacted soil can act to restrict root development and, in addition, limit the infiltration of water and air into the rooting zone. In some areas, compaction may limit soil water content and result in soil water deficits, whereas in poorly drained areas it may eliminate the large soil pores that allow for aeration and root respiration (Utzig and Herring 1974). Photo 7 illustrates the effect of a compacted skidroad on regeneration. The trees on the skidroad surface are smaller and have yellowish-brown foliage, whereas the trees on the fill slope and the adjacent unlogged area are healthy and growing vigorously.

Soil compaction, in conjunction with the removal of organic matter, reduces the infiltration capacity of the soil on road surfaces and may enhance overland flow. With reduced infiltration, the amount of water entering the soil is also reduced. This situation can result in site deterioration because less moisture is available for plant growth (Silen and Gratkowski 1953). Where surface erosion has occurred, the removal of the fine-textured soil results in a reduced cation exchange capacity and the presence of an erosion pavement (see Photos 8 and 9), making the site even more harsh for the re-establishment of vegetation (Wilford 1975).

2.4 Erosion

Surface erosion is the detachment and transport of individual soil particles by water, wind, ice and/or gravity. Exposure of mineral soils to the erosive elements, along with reduction of infiltration capabilities due to compaction and loss of organic matter, all lead to various degrees of erosion following construction of roads, trails and landings. Water erosion is accentuated by the interception and diversion of normal downslope water movement. If left unchecked, the erosion will progress through the stages of splash erosion, sheet erosion, rill erosion and finally gully erosion (see Photos 10-12).

By measuring changes in slope profile, Dyrness (1970) found a 1.14 cm soil loss from erosion over the first winter after road construction in Oregon. Soil displacement by dry ravel over the subsequent summer was almost as great, amounting to 1.02 cm. The first-year soil loss and/or displacement accounted for 2.16 cm of slope profile change or an approximate volume of 200 m^3/ha. After 5 years, the annual soil loss from the road site was 0.51 cm, still accounting for a soil loss of 50 m^3/ha of exposed slope (Dyrness 1970).

The potential impacts of surface erosion on the site are:

1. reduction of site productivity due to loss of the more fertile fine soil components;
2. hindrance or prevention of regeneration due to abrasion, removal of supporting soil components, or physical displacement of the seedling;
3. destruction of improvements such as roads, including reduction of the drainage capacity of road ditches and culverts and the undermining of road surfaces; and
4. sedimentation of lakes, reservoirs and rivers, with resultant degradation of water quality, reduced fisheries values, growth of bothersome aquatic plants and loss of reservoir water storage capacity.

2.5 Slope Failure

Slope failure, or mass wasting, is the downslope movement of a soil mass, a result of gravitational stresses exceeding soil strength. Slope failures occur in a variety of forms, from slow but steady dry ravelling (Photo 13) to abrupt and massive debris avalanches (Photos 14 and 16). Mass wasting may be extensive on steep terrain and may persist for many years after an initial triggering disturbance, such as road construction (Swanston and Swanson 1976). Photo 15 illustrates several skidroads that were constructed through an open talus slope. Minor debris slides have already occurred and may cause a large portion of the site to revert back to open talus. Slope failures are often associated with inadequate road drainage and with the distruption of the basic slope equilibrium by road and skidroad construction. Deep deposits of fill and sidecast material may overload the slope and become especially unstable when saturated with water (Photo 17). The inclusion of snow and/or organic debris in the fill material aggravates instability. Slumping and raveling of cutbanks often result from slope undercutting by deep gouges into the hillside, removing support (Photo 18). Susceptibility to failure often increases several years after logging as the structural root network begins to decompose. Slope failures produce many of the same negative impacts on the site as does surface erosion. The main difference is that the results are usually much more sudden and dramatic.

3 IMPACT ON REFORESTATION

The removal of organic matter, compaction, distruption of ground water flows, erosion, and mass wasting all contribute to render many roads, trails and landings inhospitable for growing. Landings are a constant reminder of the potential for site degradation. Photos 19 - 21 show that even the benefits of winter logging, plus various periods of time, cannot heal these scars.

Reductions in stocking height growth and volume have been noted on compacted skidroads (Steinbrenner and Gessel 1955; Youngberg 1959) (see Photo 7). Smith and Wass (1979) found significant reductions in site quality from deep disturbance, such as skid trails on soils that are either alkaline and medium to fine-textured, or acid and coarse-textured. On these soils, reductions in site quality based on reduced height growth prorated over the whole clearcut were estimated as high as 15% for subalpine fir and 12% for Engelmann spruce at an age of 12 years. The same study also demonstrated a delay in stocking of conifers on skidroad surfaces compared with that in adjacent logged areas. This was partly attributed to the complete removal or burial of seed, combined with a lack of shade.

Although the initial growth of seedlings on the fill slope of skid roads appears favorable, this may be of short duration. The increased microbial activity generated by mixing the organic matter and exposing the soil to sunlight produces a high nutrient availability. This activity, however, depletes the organic matter. With our anticipated rotations of 60 - 80 years, it is expected that the organic matter content will continue to decline, never having sufficient time to rebuild to former levels. In a Scandinavian study, seedlings on disturbed ground showed increased growth for the first 25 years, but they were overtaken after 40 years by trees on undisturbed ground in the control plots (J.P. Kimmins, pers. comm.). Most studies on reforestation have used the growth of trees on undisturbed surfaces as the basis for comparison with tree growth on disturbed surfaces, such as skid trails and landings. Such information may underestimate the total growth losses if the road or trail construction has caused an overall decrease to site productivity to the entire site. This might occur through loss of seepage water, redirection of subsurface flow off the site, and loss of rooting medium for trees located close to cutslopes. Photo 22 illustrates the reduced stocking and slower growth often found on skidroads. The skidroad in Photo 23 has been taken over by mosses, horsetail and grasses because of the excessive moisture which resulted from interception of seepage water. The compacted, nutrient-poor soil of the skidroad in Photo 24 is supporting only the growth of alder.

4 METHODS

Continuous trip transects were measured on five representative sites varying in slope, time since logging, and location within the eastern portion of the Forest District. The information from four additional transects on the Winnifred Creek site was provided by Riverside Forest Products Ltd. The short length of this study and the lack of any manpower assistance dictated that the survey methods be simple and quick. Transects were run perpendicular to the contours with a hip chain. The point of commencement was objectively selected to provide a sampling that was representative of the site. Distances between disturbed locations were measured, and at the intersection of the transect with each skidroad, the following were measured:

- skidroad surface width;
- cutslope height;
- grade;
- sideslope (averaged on even terrain);
- any noticeable erosion or slope failure; and
- soil classification and texture.

Disturbance was considered to be any gouges or deposits exceeding 10 cm. This was an arbitrary figure, selected to approximate the depth at which the productivity may be affected on soils typical of the study areas. It was recognized that shallow or light disturbance may be advantageous to tree establishment, provided it does not predispose the soil to erosive forces.

After the transect was measured, the balance of each cutblock, along with 12 other cutblocks, were examined on a "walk through" basis. Any notable signs of site degradation, along with any good or poor examples of skidding system construction, were recorded.

5 RESULTS

For the sake of brevity, the maps and transect profiles for each study area have been omitted from the original report dated August 23, 1984.

5.1 Study Area No. 1

A. DESCRIPTION

OPENING NO.:	82L/l-f - 33
LOCATION:	Railroad Creek - Pinnacles
ELEVATION:	1450 m
ASPECT:	South
SIZE:	21 ha
SLOPE:	10-80%
LOGGED:	1980, 81, 83; winter & fall; hand felling; rubber-tired (R/T) skidders
POST-LOGGING TREATMENT:	broadcast burn 1983
BIOGEOCLIMATIC UNIT:	ESSFm (upper elevations) ICHm2 (lower elevations)
LANDFORM:	morainal blanket with some colluvial and glaciofluvial veneers
SOILS:	Dystric Brunisol; gravelly-sandy loam
ORGANIC LAYER:	5-20 cm
MOISTURE REGIME:	submesic
NUTRIENT REGIME:	submesotrophic

B. DISTURBANCE SURVEY

TRANSECT LENGTH:	251 m
AVERAGE TRANSECT SLOPE:	59%
DISTURBANCE LEVEL[1]:	60.6%
AVERAGE SKIDROAD SURFACE:	4 m
AVERAGE CUTSLOPE HEIGHT:	2.5 m
AVERAGE SKIDROAD/ROAD SPACING:	20.7 m (horizontal distance) 25.5 m (slope distance)

C. COMMENTS:

As Photos 26 and 27 illustrate, large portions of this cutblock are now occupied by deeply disturbed ground that is continuous from skidroad to skidroad. What little organic material was left has been consumed largely by the broadcast burn. Poor planning of skidroads is apparent in Photo 25. A small creek that flowed parallel to the western boundary has been crossed several times by a figure "8" pattern of skidroads, causing diversion and subsequent sheet erosion and ponding. A naturally occurring, larger percentage of fines (silts and clays) is present in the soil on the lower portions of the slope, and thus contributes to ravel stability and water holding capacity. However, the finer material is more susceptible to erosion, and with the shallow depth to bedrock, mantle failure is a distinct possibility. The natural distribution of gravel and sand is much grater towards the top of the slope. This material will be more subject to dry ravelling. Successful regeneration of this site may be limited by lethal temperatures resulting from blackened organic layers, a lack of shade, and the southern exposure. Surface drying, a lack of nutrients and erosion may also affect seedling survival and/or performance.

The disturbance transect indicated a disturbance level of 60.6%. This does not include the shallower disturbance between skidroads resulting from skidding activities. Furthermore, this is not the most heavily disturbed portion of the block. On the other hand, the cutblock also occupies the valley bottom where few skidroads were constructed. This points out the need to stratify an area before trying to carry out an accurate assessment of disturbance.

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[1] Disturbance is defined as any gouges or deposits exceeding 10 cm (see Section 4).

5.1 Study Area No. 2

A. DESCRIPTION

OPENING NO.:	82L/I-b-20
LOCATION:	Bruer Creek
ELEVATION:	1300 m
ASPECT:	Northeast
SIZE:	34 ha (logged at time of survey) 40 ha (total)
SLOPE:	18-61%
LOGGED:	1980; winter hand felling; small cat skid
POST-LOGGING TREATMENT:	none to date
BIOGEOCLIMATIC UNIT:	ICHa1
SOILS:	sandy loam
ORGANIC LAYER:	6 cm
NUTRIENT REGIME:	mesotrophic
MOISTURE REGIME:	mesic to submesic (on upper slope)

B. DISTURBANCE SURVEY

TRANSECT LENGTH:	226 m
AVERAGE TRANSECT SLOPE:	18-61%
DISTURBANCE (>10 cm) LEVEL:	17%
AVERAGE SKIDROAD SURFACE:	1.1 m (61% slope)
AVERAGE CUTSLOPE HEIGHT:	0.9 m (61% slope)
AVERAGE SKIDROAD/ROAD SPACING:	17.1 m (horizontal distance) 20.0 m (slope distance - 61% slope)

C. COMMENTS:

This cutblock (Photo 28) is an example of the results that can be obtained by restricting skidding to small crawler tractors (<58 kw and <3.1 m blade width). As Photo 29 illustrates, the average trail surface is only 1.1 m and the depth of cut 0.9 m. This compares with an average width of 3.4 m and depth of cut of 1.8 m obtained on the other study areas using rubber-tired skidders.

It should be mentioned that part of the reduction in disturbance is attributable to operating on the snowpack. Comparative reductions may also be realized with rubber-tired skidders if the snow is heavy enough to be used as part of the running surface.

The center landing in this block intercepts a small creek. As Photo 30 illustrates, the creek was diverted down the haul road where it is cutting away at the road surface.

5.3 Study Area No. 3

A. DESCRIPTION

OPENING NO.:	82E/15-h-58
LOCATION:	Winnifred Creek
ELEVATION:	1350 m
ASPECT:	South
SIZE:	67 ha
SLOPE:	30-70%
LOGGED:	1983, 84; winter hand felling; R/T skid
POST-LOGGING TREATMENT:	none to date
REGENERATION:	NSR
BIOGEOCLIMATIC UNIT:	MSb2
LANDFORM:	morainal blanket & veneer
SOILS:	Dystric Brunisol; loamy sand
ORGANIC LAYER:	1-2 cm
MOISTURE REGIME:	subxeric
NUTRIENT REGIME:	oligotrophic

B. DISTURBANCE SURVEY

Disturbance by Strip Number

Strip No.	Disturbance Length (m)	Transect Length (m)	Disturbance Level (%)
1	81	440	18
2	208	570	36
3	180	570	32
4	137	380	36
		1960	

Disturbance by Slope Category

Slope %	Disturbance Length (m)	Transect Length (m)	Disturbance Level (%)
26-35	19	40	47.5
36-45	253	940	26.9
46-55	7	330	2.1
56-65	255	520	49.0
66	26	130	20.0
		1960	

AVERAGE SKIDROAD SURFACE: 3.0 m

AVERAGE CUTSLOPE HEIGHT: 1.2 m

AVERAGE SKIDROAD/ROAD SPACING:
(Strip #2 excluding ridgetops)
(25.3 m (horizontal distance)
(32.0 m (slope distance - 70% slope)
(25.0 m (slope distance - 40% slope)

C. COMMENTS:

This was the only block studied on which potential disturbance problems were jointly identified by the Ministry of Forests and Lands and the licensee prior to logging. Some of the harvesting objectives were:

- to minimize the intensity of skidroads;
- to minimize the size of skidroads, with a maximum depth of cut set at 1 m; and
- to complete harvesting prior to the following spring (for control of the Mountain Pine Beetle).

In order to allow flexibility, the licensee was permitted to select the machinery and methods that would best accomplish the objectives. Unfortunately, as sometimes happens, the best of plans are not always followed by the people who are expected to implement them. Photos 31-35 are visible proof of the overpowering effect of economics on our harvesting methods. Although an effort was made to minimize disturbance on this site, it was largely negated by the use of full-size crawler tractors and rubber-tired skidders in combination with a loose, dry snowpack.

A permanent loss of site productivity is certain to result from the excessive disturbance on this site. Of the areas examined, this cutblock is most susceptible to site degradation, being the driest, least fertile and most unstable. The most obvious impacts are the loss of organic matter, distruption of ground water flows, and mass wasting.

Photo 33 illustrates the effects of poor skidroad layout, compounded by the upgrading of some trails to summer standards because harvesting was not finished on schedule. Photo 35 shows a skidroad constructed with a 50% grade, which could easily become a drainage channel for any surface runoff.

It is interesting to note that higher disturbance levels do not necessarily coincide with steeper slopes, especially when the terrain is broken as in this cutblock. This is due in part to the fact that the operator can often fell the timber on the steeper areas to skidroads located on less steep terrain. Landings with their associated converging skidroads are also located on less steep sites.

As a final note, it should be mentioned that the licensee did achieve some success with minimizing disturbance on the less steep, eastern portion of this cutblock. Snow was used as part of the skidroad surface, thus keeping the depth of cut to a minimum.

5.4 Study Area No. 4

A. DESCRIPTION

OPENING NO.: 82L/I-f-31

LOCATION: Marsh Lake

ELEVATION: 1475 m

ASPECT: East

SIZE: 24 ha

SLOPE: 60-90%

LOGGED: 1983; hand fell, R/T skid

POST-LOGGING TREATMENT: none to date

REGENERATION: NSR

BIOGEOCLIMATIC UNIT: ESSFm (upper elevations)
ICHm2 (lower elevations)

LANDFORM: colluvial

SOILS: Dystric Brunisol;
gravelly-loamy sand

MOISTURE REGIME: subxeric to submesic

NUTRIENT REGIME: submesotrophic

B. DISTURBANCE SURVEY

TRANSECT LENGTH: 139.6 m

AVERAGE TRANSECT SLOPE: 74%

DISTURBANCE (>10 cm) LEVEL: 51%

AVERAGE SKIDROAD SURFACE: 3.7 m

AVERAGE CUTSLOPE HEIGHT: 2.9 m

AVERAGE SKIDROAD/ROAD SPACING: 20.9 m (horizontal distance)
20.0 m (slope distance)

C. COMMENTS

When viewed from the bottom, as with most sites, the small patches of undisturbed greenery on this block tend to obstruct the massive areas of disturbance (Photo 36). Bedrock has been exposed in many locations (Photo 37) and most of the skidroads are nothing but rocks and gravel (Photos 38 and 39). Although very stable, even rock will start to roll downhill on extreme slopes such as these.

The natural open talus shown in Photo 40 is a good indication of the origin of the soils on this site. This type of colluvial material is not only nutrient poor, but it is also very prone to drying out once the upper soil and organic layers have been removed. Plantation re-establishment problems and poor seedling performance should consequently be anticipated.

5.5 Study Area No. 5

A. DESCRIPTION

OPENING NO.: 82L/16-d-4

LOCATION: Derry Creek

ELEVATION: 1280 m

ASPECT: Northwest

SIZE: 25 ha

SLOPE: 50-70%

LOGGED: 1976, 78; winter;
hand fell, R/T skid

POST-LOGGING TREATMENT:	spot burned, 1980
BIOGEOCLIMATIC UNIT:	ICHw
SOILS:	sandy loam
ORGANIC LAYER:	5-10 cm
MOISTURE REGIME:	mesic
NUTRIENT REGIME:	mesotrophic

B. DISTURBANCE SURVEY

TRANSECT LENGTH:	257.5 m
AVERAGE TRANSECT SLOPE:	60%
DISTURBANCE (>10 cm) LEVEL:	16.7%
AVERAGE SKIDROAD SURFACE:	2.9 m
AVERAGE CUTSLOPE HEIGHT:	1.4 m
AVERAGE SKIDROAD/ROAD SPACING:	25.7 m (horizontal distance) 30.0 m (slope distance)

C. COMMENTS

This block is an example of how the impact of logging steep areas can be minimized, even with conventional equipment (Photo 41). Skidroad layout was well planned, and at 30 m, spacing was the maximum of all areas examined. Disturbance has less of an impact on these deeper, more fertile soils, and with the abundant moisture on a moderately well-drained site, reforestation should not be a problem.

Since the fill portions of these skidroads were stable, well vegetated, and difficult to delineate, they were not measured as part of the disturbance level. The fact that this area was winter-logged no doubt contributed to a lower overall disturbance level. The average skidroad surface width was 2.9 m (Photo 42). Since most rubber-tired skidders require a 3.5 to 4.0 m running surface, it is apparent that snow made up the balance of the skidroad width.

5.6 Study Area No. 6

A. DESCRIPTION

OPENING NO.:	82L/16-c-1
LOCATION:	Blanket Mountain
ELEVATION:	1650 m
ASPECT:	West
SIZE:	63 ha
SLOPE:	25-50%
LOGGED:	1977,78; winter; hand felling R/T skid
POST-LOGGING TREATMENT:	spot burn, 1979
REGENERATION:	NSR
BIOGEOCLIMATIC UNIT:	ESSFwl

SOILS: sandy loam
ORGANIC LAYER: 7-12 cm
NUTRIENT REGIME: mesotrophic
MOISTURE REGIME: mesic

B. DISTURBANCE SURVEY

DISTURBANCE (>10 cm) LEVEL: 25.9%
AVERAGE SKIDROAD SURFACE: 3.5 m
AVERAGE CUTSLOPE HEIGHT: 1.2 m
AVERAGE SKIDROAD/ROAD SPACING: 26.0 m (horizontal distance)
28.3 m (slope distance)

C. COMMENTS:

The deeper, richer soils and moderate slope of this site served to minimize the impact of the ground skidding systems that were used (Photo 43). Nonetheless, the nutrient-poor soils that have been exposed on the wide skidroad surfaces will undoubtedly diminish the growth of future regeneration (see Photo 44). Since the fill portions of these skidroads were stable, well vegetated and difficult to delineate, they were not measured as part of the disturbance level.

6 DISCUSSION

Table 1 summarizes the results of disturbance surveys on the six study areas. There is no obvious relationship between slope and disturbance levels, no doubt because other factors, such as season of logging, topography, soil type and quality of planning, also come into play.

The most visible difference between the skidding systems examined is that between the small crawler tractors utilized in study area #2 and the conventional rubber-tired skidders used in the other areas. The disturbance level, skidroad surface width and cutslope height in area #2 were all less than half that in the other areas. McMorland (1980) found similar results; in fact, site disturbance studies showed that areas logged by small tractors have approximately one-third less disturbance than areas with trail networks built by larger crawlers in summer or winter. Skidroad spacing on area #2 was the least of any of the study areas. However, spacing is more a function of tree height or convenience, rather than machine type. McMorland (1980) obtained an average skidroad spacing of 32.1 m (horizontal distance) on sites logged by small tractors, as compared to an average of 27.0 m for areas prepared by large tractors.

A draft Ministry of Forests and Lands proposal for harvesting guidelines in the Kamloops Forest Region specified a maximum disturbance level of 15% for sites with low to moderate sensitivity.[2]

The establishment of disturbance levels is valuable in that it allows the licensee the flexibility to select the equipment and system to achieve the stated objective. However, three important points should be kept in mind:

1. Cutblocks should be stratified by slope class before maximum disturbance levels are applied. Otherwise, an unacceptable level of disturbance on a steep part of a cutblock could be averaged down to an acceptable level it is grouped with the flatter portion of the block.

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[2] Mitchell, W.R. 1984. Draft proposal of guidelines for timber harvesting practices in the Kamloops Forest Region. B.C. Min. For., Kamloops, B.C. Unpublished report. 8 p.

TABLE 1. Summary of disturbance details from study areas

Study Area Location	Slope (%)	Disturbance (%)	Skidroad Surface (m)	Cutslope Height (m)	Skidroad Spacing (m Slope Distance)
1 Pinnacles	59	60.6	4.0	2.5	25.5
2 Bruer Creek[a]	61	17.0	1.0	0.9	20.0
3 Winnifred Creek	26-35	47.5			
	36-45	26.9			
	46-55	2.1			
	56-65	49.0			
	66	20.0	3.0	1.2	28.5
Average	50	29.1			
4 Marsh Lake	74	51.0	3.7	2.9	26.1
5 Derry Creek	60	16.7[b]	2.9	26.1	30.0
6 Blanket Mountain	41	25.9[b]	3.5	1.2	28.3
AVERAGE	57.5	33.3	3.0	1.7	26.4

[a] Small crawler tractor skidding.

[b] Does not include fill slope disturbance.

2. It is possible to achieve stated disturbance levels while still causing major environmental degradation. An example would be the construction of a few very large skid trails. The disturbance level may be low because few trails were constructed, but huge unstable cuts and fills may be environmentally unacceptable. It is thus important to provide specific information about disturbance by relating guidelines for harvesting systems and equipment types to site sensitivity. Specific guidelines for depth of cut, grade, and minimum spacing of skidroads is important for the same reason.
3. Most operational people have difficulty relating to disturbance percentages. They need to know things such as the type of equipment they can use, the spacing between skidroads, the size of skidroads and the size of landings.

The information in Table 1 indicates that a disturbance level of 15% might be difficult to attain with conventional ground harvesting systems on slopes greater than 40%. One alternative is cable harvesting. Photos 45 and 46 dramatically illustrate the difference between high lead and skidder logging. Two roads traverse the former area; 21 skidroads traverse the latter area.

The most obvious method of reducing site disturbance is the use of alternative types of equipment for yarding such as small crawler tractors, low ground pressure skidders, cable, helicopters or horses. Where these are not practical, it may be possible to achieve similar results with conventional skidders by modifying the harvesting system. Under suitable snowpack conditions, skidroads can be constructed mostly from snow. Alternatively, random skidding may be successful on slopes up to 60% if the soil has a high bearing strength, the stumps are low and the safety margin is acceptable. Occasional return trails may be required to take the skidder to the top of the hill, enabling it to transport the load straight down the slope without the use of contour skidroads.

The use of alternative yarding equipment or modified harvesting systems usually receives considerable resistance because of the lower productivity and/or higher costs. What must be considered is the relative value of maintaining the natural productivity of forest sites as well as the quality and integrity of other resource values; environmental degradation is usually irreversible. There is a large amount of steep country in the Vernon Forest District. It is difficult to see how any licensee could manage his operating area in a responsible manner without the use of alternative harvesting methods or equipment.

7 CONCLUSIONS AND RECOMMENDATIONS

From the information provided in this report, the photographs and the study results, it should be apparent that the conventional ground skidding systems in use on many of the steep slopes in the Vernon Forest District are having a detrimental impact on the environment. Site degradation and productivity losses are resulting from excessive disturbance, which causes loss of organic matter, interruption of normal downslope water movement, soil compaction, erosion and slope failure. The forest land base is much too important to jeopardize for short-term economic gains; consequently strong measures should be implemented:

- First, it is recommended that the subject of yarding equipment and systems be addressed and resolved at the pre-harvest prescription stage. All too often it has been saved until the logging plan stage, where short-term availability becomes more important than suitability.
- Second, it is recommended that the following information be provided whenever skidroad construction is anticipated as part of a harvesting proposal:
    1. a detailed map of sites and slope classes broken down to <30%, 30-45%, 46-60%, >60%;
    2. a map of the proposed skidroad construction areas;
    3. the maximum proposed disturbance level (by site sensitivity);
    4. the maximum depth of cut on skidroads; and
    5. the minimum skidroad spacing distance.
- Third, it is recommended that guidelines be established for harvesting systems and the construction of skidroads and landings. The objective should be to maintain the natural productivity of forest sites and prevent serious damage to the natural environment.
- The final recommendation is that the B.C. Forest Service define the amount and type of disturbance that is considered acceptable. Once standards have been set, existing legislation should be amended to permit enforcement of those standards. As part of this process, it is important that the costs of protecting the land base be recognized. Under the present stumpage appraisal system, there is little incentive for licensees to incur added expenses to protect the environment on Crown lands.

8 ACKNOWLEDGEMENTS

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PHOTO No. 1
Opening No. 82L/16-d-7
DERRY CREEK
Logged 1979-1980

Displacement or burial of organic matter resulting from skidroad construction.

PHOTO No. 2
Opening No. 82L/1-f-31
Logged 1983

Loss of organic matter resulting from skidroad construction.

PHOTO No. 3
Opening No. 82E/15-h-56
WINNIFRED CREEK
Logged 1983,84

Loss of organic matter resulting from skidroad construction.

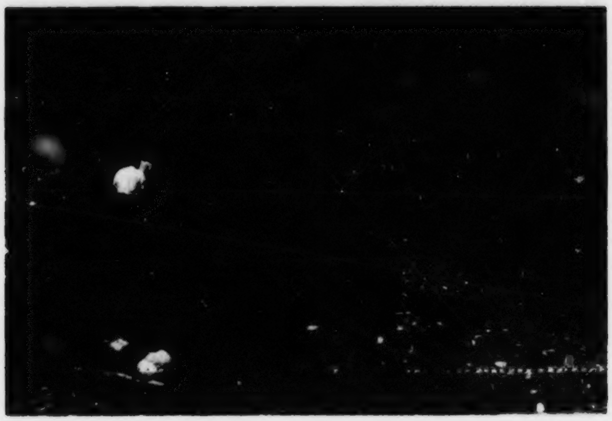


PHOTO No. 4
Opening No. 82L/10-h-36
HOUND CREEK
Logged 1970

Intercepted and redirected subsurface water flow.

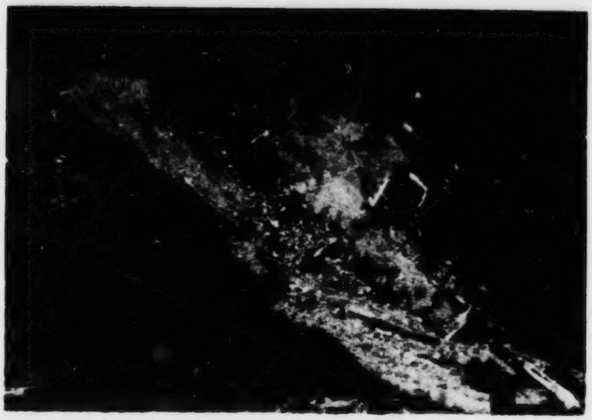


PHOTO No. 5
Above 48½ km
SUGAR FOREST RD.
Logged 1974

Cut and fill slope failure due to intercepted surface and subsurface water flow.

PHOTO No. 6
Opening No. 82L/1-f-33
RAILROAD CR.-PINNACLES
Logged 1980,81,83

Diverted surface water flow.

PHOTO No. 7
S.W. and contiguous to
A07295-Railroad Cr.
Logged — estimate early 1960's

Regeneration showing stress on compacted skidroad surface.

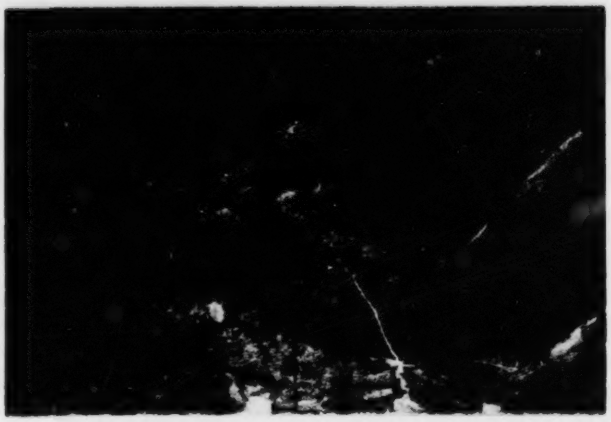


PHOTO No. 8
Opening No. 82L/16-c-1
BLANKET MOUNTAIN
Logged 1977,78

Erosion pavement.

PHOTO No. 9
Opening No. 82L/16-d-7
DERRY CREEK
Logged 1979,80

Erosion pavement.

PHOTO No. 10
Opening No. 82E/15-h-36
WINNFRED CREEK
Logged 1979

Erosion from normal downslope water movement which has been intercepted, diverted, and accumulated by skid rail, road and landing construction.

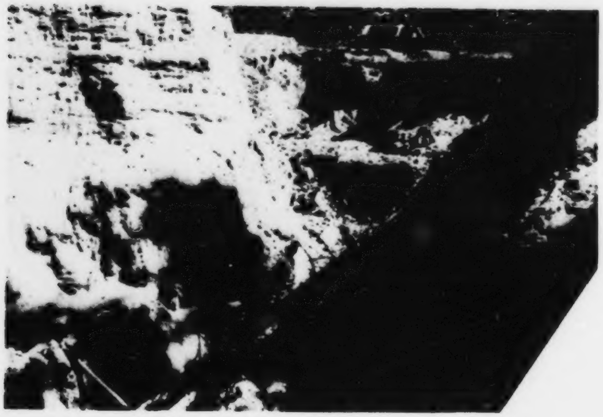


PHOTO No. 11

Accumulated water from ditch in Photo 10 had sufficient force to wash out road and create massive gully leading into a tributary of Winnifred Creek.

PHOTO No. 12
Opening No. 82L/16-d-14
DERRY CREEK
Logged 1982, 83

Erosion resulting from interception of a water course by a landing, which led to ponding and subsequent diversion down this skidroad.

PHOTO No. 13
Opening No. 82E/15-h-36
WINNIFRED CREEK ROAD
- 1 km WEST:

Dry ravelling.

PHOTO No. 14
Opening No. 82L/16-d-7
DERRY CREEK

Debris avalanche resulting from skidroad on a 90% slope.

PHOTO No. 15
Opening No. 82L/1-f-17
RAILROAD CREEK-PINNACLES
Logged 1977

Skidroads constructed through open talus. Some minor debris slides. Potential for portions of site to revert back to talus.

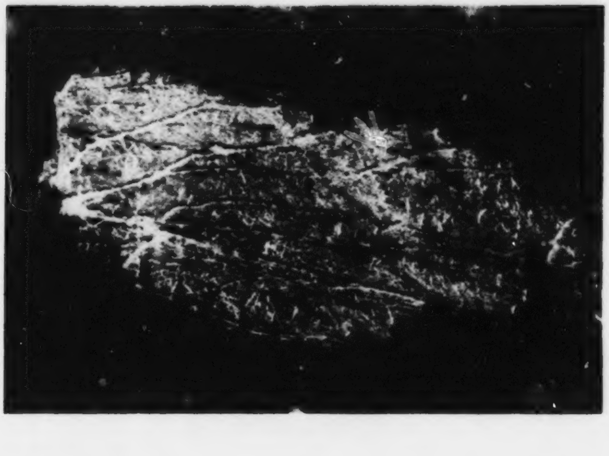


PHOTO No. 16
Opening No. 82L/16-d-7
DERRY CREEK
Logged 1979

Debris avalanche resulting from skidroad construction on a 90% slope.

PHOTO No. 17
Opening No. 82L/10-b-38
SIMARD CREEK
Logged 1983,84

Debris torrent resulting from rapid downslope movement of saturated fill material within an existing drainage channel.

PHOTO No. 18
Opening No. 82L/1-f-31
MARSH LAKE
Logged 1983

Slumping of cutbank due to undercutting of skidroad and subsequent ravelling.

PHOTO No. 19
Opening No. 82L/10-h-36
HOUND CREEK
Logged 1970

Landing is devoid of regeneration even after 14 years. Adjacent area is overstocked with healthy conifers.

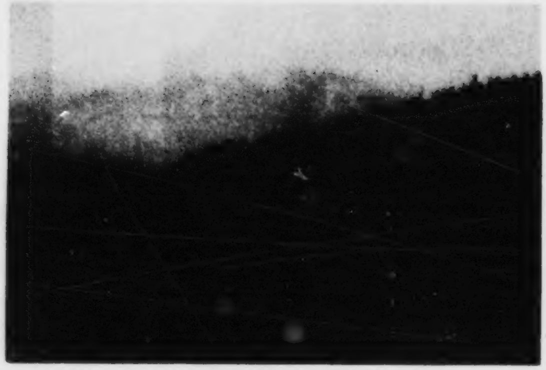


PHOTO No. 20
Opening No. 82L/16-c-1
BLANKET MOUNTAIN
Logged 1977,78

Land still has no vegetation after 6 years.

PHOTO No. 21
Opening No. 82L/16-d-14
DERRY CREEK
Logged 1982,1983

Ponding caused by constructing landing over a water course will prevent establishment of conifers.

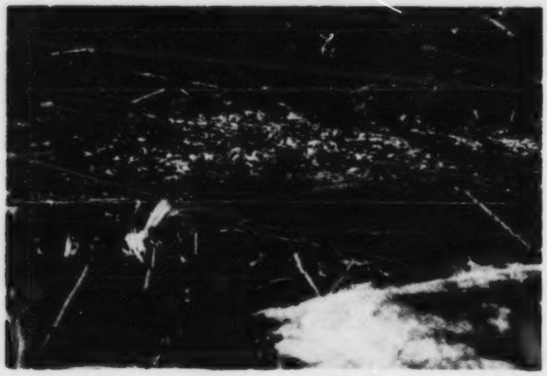


PHOTO No. 22 (See also No.4)
Opening No. 82L/10-h-36
HOUND CREEK
Logged 1970

Insufficient stocking on skidroads. Height less than ¼ that on undisturbed sites.

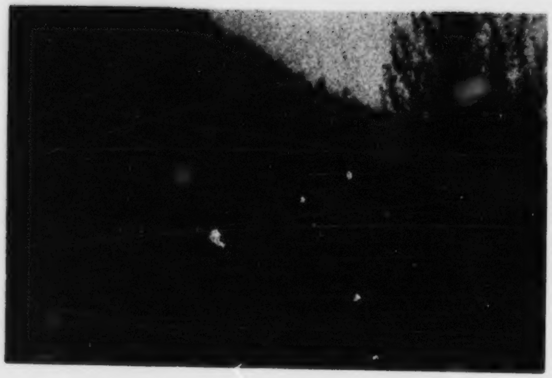


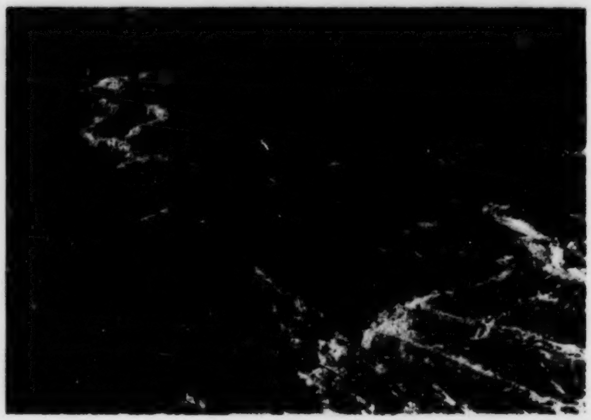
PHOTO No. 23
SALVAGE-LOGGED BURN AT
JUNCTION OF RAILROAD
AND MONASHEE CREEKS.
Burned 1967

Skidroad fully occupied by mosses, horsetail and grasses due to excessive moisture resulting from interception of seepage water.

PHOTO No. 24
Opening No. 82L/9-d-41
CURWIN CREEK-SAWTOOTH
Logged 1973

Compacted, nutrient-poor parent material on skidroad. Vegetation is restricted largely to alder.

PHOTO No. 25
Opening No. 82L/1-f-33
STUDY AREA No.1
RAILROAD CREEK-PINNACLES



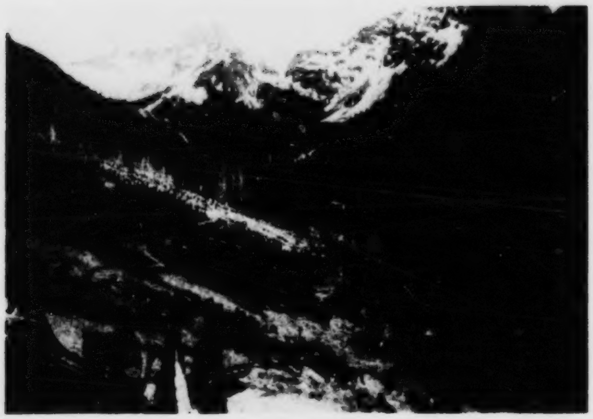


PHOTO No. 26
Opening No. 82L/1-f-33

Mid-slope. Disturbance is continuous in some areas.

PHOTO No. 27
Opening No. 82L/1-f-33

Typical skidroad showing excavation into rocky parent material.

PHOTO No. 28
Opening No. 82L/2-b-20
STUDY AREA No. 2
BRUER CREEK

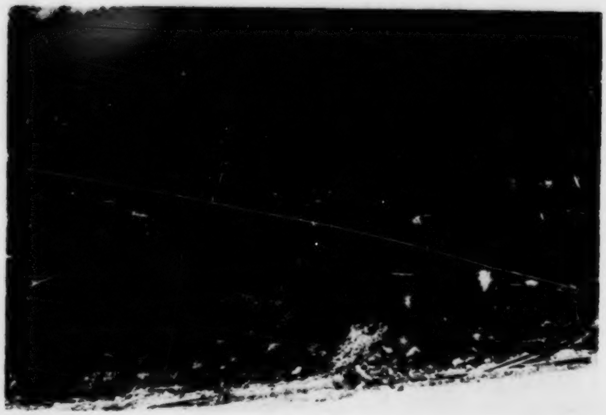


PHOTO No. 29
Opening No. 82L/2-b-20

Skidroad for "small cat" skidding.

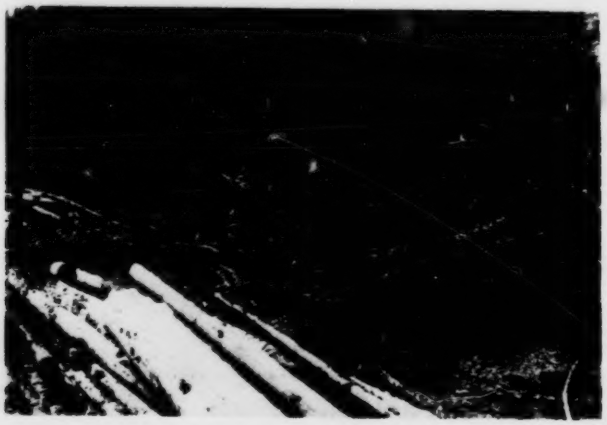


PHOTO No. 30
Opening No. 82L/2-6b-20

Small creek intercepted by landing and diverted down haul road.

PHOTO No. 31
Opening No. 82E/15-h-58
STUDY AREA No.3
WINNIFRED CREEK

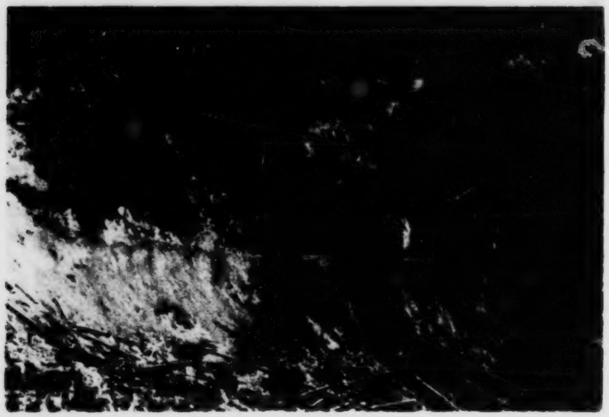


PHOTO No. 32
Opening No. 82E/15-h-58

Extensive soil disturbance from road construction.

PHOTO No. 33
Opening No. 82E/15-h-58

Intensive network of large skidroads.

PHOTO No. 34
Opening No. 82E/15-h-58

Skidroad excavation in sandy soil types.

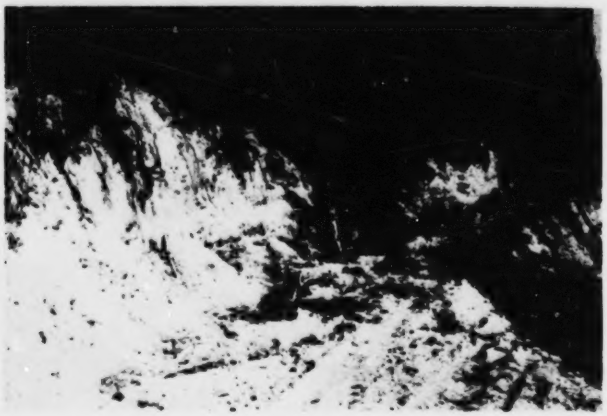


PHOTO No. 35
Opening No. 82E/15-h-58

Fifty percent skidroad grade on soils with low bearing strength.

PHOTO No. 36
Opening No. 82L/1-f-31
STUDY AREA No.4
MARSH LAKE

PHOTO No. 37
Opening No. 82L/1-f-31

Skidroad.

PHOTO No. 38
Opening No. 82L/1-f-31

Skidroad.

PHOTO No. 39
Opening No. 82L/1-f-31

Skidroad.

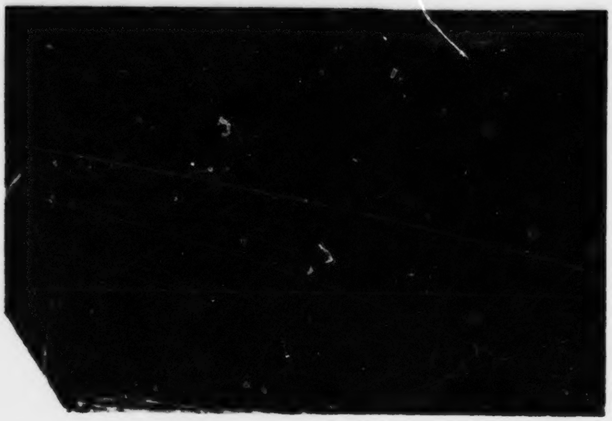


PHOTO No. 40
Opening No. 82L/1-f-31

Natural open talus, indicative of soil origin.

PHOTO No. 41
Opening No. 82L/16-d-4
STUDY AREA No. 5
DERRY CREEK

PHOTO No. 42
Opening No. 82L/16-d-4
STUDY AREA No. 5

Typical skidroad.

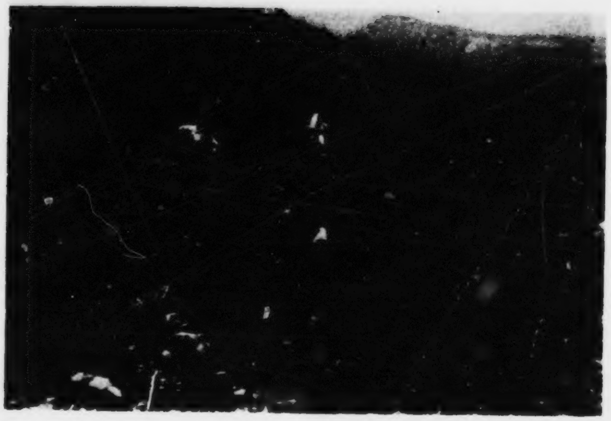


PHOTO No. 43
Opening No. 82L/16-c-1
STUDY AREA No. 6
BLANKET MOUNTAIN

PHOTO No. 44
Opening No. 82L/16-c-1

Typical skidroad.

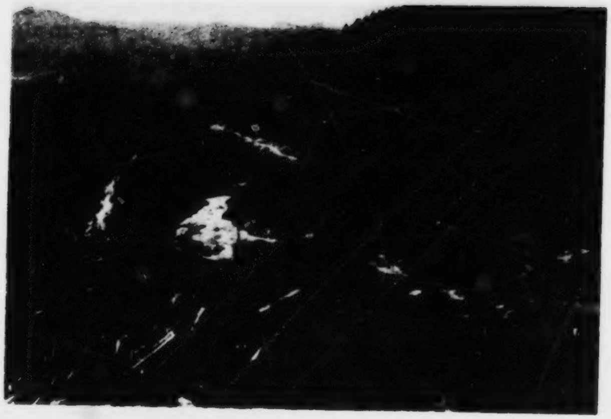


PHOTO No. 45
Opening No. 82L/10-h-7
IRON CREEK

Cable logged with single road through center of block.

PHOTO No. 46
Opening No. 82L/1-f-1
MARSH LAKE

Conventional ground skidding with more than 21 skidroads.

SESSION 1-1 TIMBER HARVESTING

A COMPARISON OF SOIL DISTURBANCE CAUSED BY CABLE AND SMALL TRACTOR LOGGING

W.J. Watt[1]
R.K. Krag[2]

ABSTRACT

Soil disturbance was monitored on a logging trial in which allowable maximum soil disturbance levels were set at 10% of the harvested area. Areas harvested by cable systems had 10% or less disturbance. Areas harvested with small crawler tractors had 19.6 and 20.3% disturbance for summer and winter operations, respectively. Machine activity for building and using skidroads was the main difference between the amounts of tractor and cable logging disturbance. Winter skidroads had half the detrimental soil compaction of summer skidroads. Soil disturbance for winter tractor logging was reduced to 15.9% based on the reduced soil compaction.

1 INTRODUCTION

Timber harvesting on more difficult terrain is being undertaken with greater frequency and is resulting in an increase in associated economic and environmental problems. Very simply, logging costs increase on sloping terrain, and steeply sloping areas are more susceptible to environmental damage through logging disturbance. The environmental impacts associated with logging disturbance can directly affect forest productivity and may extend off-site to affect other resources.

Studies in interior British Columbia and elsewhere have shown that cable harvesting operations generally cause less detrimental yarding disturbance than conventional ground-based systems. Table 1 summarizes harvesting-related site disturbance from two such studies (Smith and Wass 1976; Schwab and Watt 1981). Some types of harvesting disturbance reduce site productivity as measured by reduced height growth and lengthened regeneration delay. In one study in interior British Columbia (Interior Cedar Hemlock Biogeoclimatic Zone in the Cariboo), the greatest site-specific growth reduction occurred on the inner disturbed part (upslope side) of skidroads where the growth of Douglas-fir and Engelmann spruce was reduced 56.9 and 34.8%, respectively, when compared to the controls growing between the skidroads (Smith and Wass 1980). By prorating all skidroad growth reductions over the entire cutblock, the authors found that harvesting disturbance resulted in 14 and 2.1% growth reductions for Douglas-fir and Engelmann spruce, respectively, based on 11 years' growth (Smith and Wass 1980).

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However, the cost of cable yarding is generally higher than that for groundskidding methods. Therefore, the challenge facing forest harvesting licensees and agency planners and foresters is to plan and apply conventional and alternative ground systems to minimize site disturbances which directly or indirectly cause on- and/or off-site damage (degradation), at a cost savings relative to cable systems.

In the Cariboo Forest Region, approximately 121 600 ha of mature timber within the Williams Lake Timber Supply Area occur on slopes >34% (Hedin 1978). Most of the steep-slope areas currently being harvested are located in the Quesnel Highlands and Cariboo Mountains, a 60 km wide belt 65 km east of Williams Lake (Figure 1), where one-third of the mature timber in the Quesnel Lake area is on slopes of 30% or more.

TABLE 1. Site occupancy by machines, interior British Columbia

Harvesting Method	**Season**	**% Occupancy**						**Source**
		Road	**Landing**	**Skidroad**	**Tail-hold**	**Other**	**Total**	
Ground-skid	S	7.6	0.6	20.5		11.1	39.8	a
	W	2.9	0.5	8.8		9.1	21.3	a
	S/W	5.6	2.3	36.0		2.7	46.7	b
High Lead	S	6.6	1.1	1.2		2.2	11.1	a
	W	5.0	0	8.7		2.7	16.4	a
Grapple	S	0	0	0	14.1	13.0	27.1	a
	W	0	0	0	11.2	9.2	21.8	a
	S/W	8.0	1.2	4.3	4.3	0	17.8	b

[a] R.B. Smith and E.F. Wass (1976).

[b] J.W. Schwab and W.J. Watt (1981).

2 THE STUDY OBJECTIVES

The study reported here was a cooperative effort involving the B.C. Ministry of Forests and Lands (MoFL), Cariboo Region; Weldwood of Canada Limited, Williams Lake Operations; and the Western Division of the Forest Engineering Research Institute of Canada (FERIC). This study of small crawler tractor and cable harvesting systems on similar areas was undertaken to (1) measure and compare the performance and costs for each logging system, and (2) determine whether the small crawler tractor system meets pre-set limits for detrimental site disturbance. Small crawler tractors were chosen as an alternative to cable logging because their smaller size could significantly reduce depths of cuts and fills in skidroads on steep slopes, and achieve logging costs per cubic metre of wood that are comparable to conventional rubber-tired skidders (McMorland 1980). This paper focuses on the second objective. A FERIC report in preparation will describe the study and results more fully.

Specific site disturbance limits set for the study were a maximum of 10% detrimental disturbance on sensitive and other site types and a maximum of 5% detrimental disturbance on very sensitive sites. "Detrimental disturbance" was defined as any activity on the soil which could directly or indirectly cause soil degradation (including mass movement, accelerated erosion, nutrient displacement, and soil compaction or puddling).

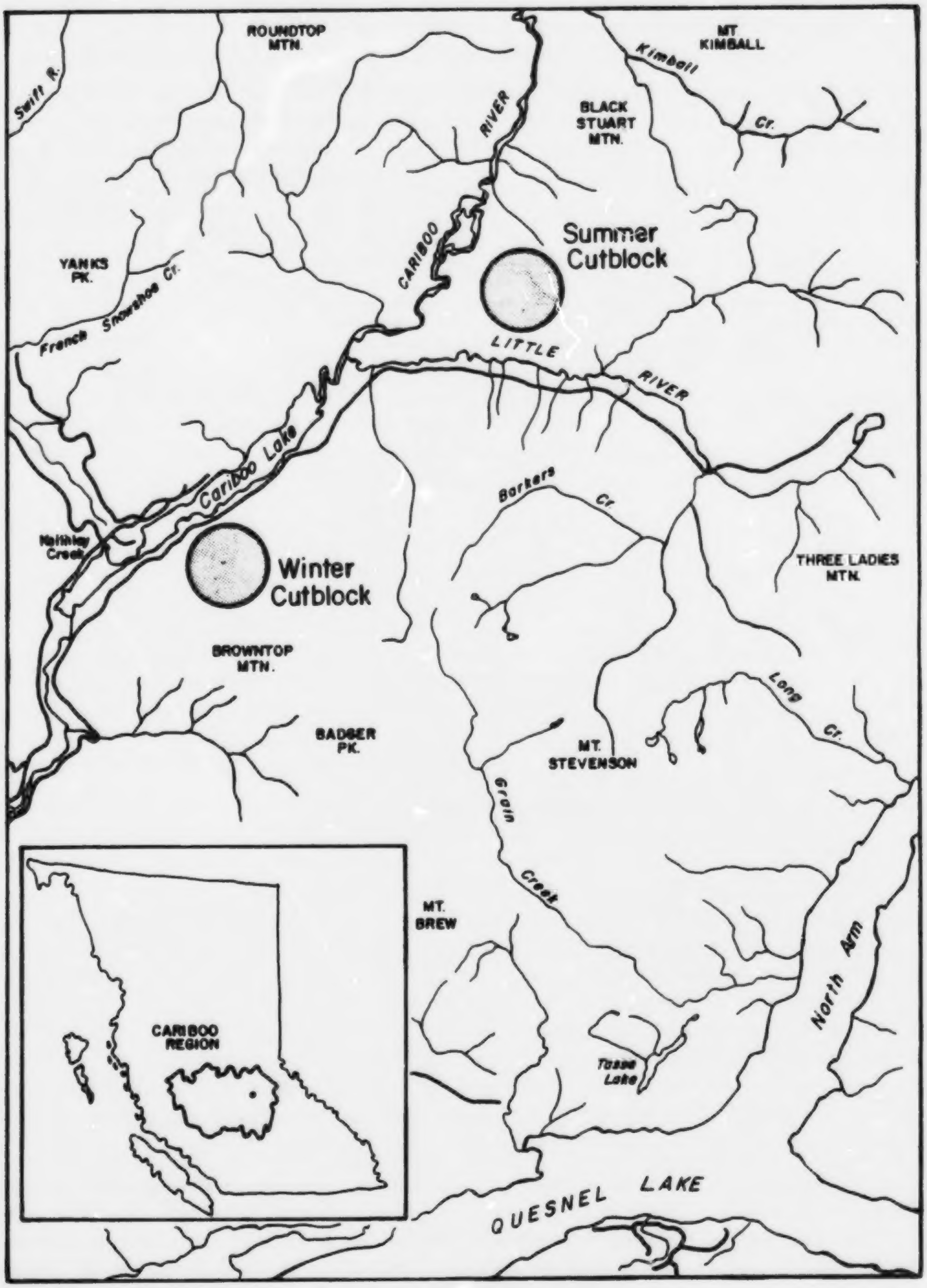

ROUNDTOP MTN.
MT KIMBALL
Kimball Cr.
Swift R.
BLACK STUART MTN.
CARIBOO RIVER
Summer Cutblock
YANKS PK.
French Snowshoe Cr.
LITTLE RIVER
Cariboo Lake
Barkers Cr.
Keithley Creek
Winter Cutblock
THREE LADIES MTN.
BROWNTOP MTN.
Long Cr.
BADGER PK.
MT. STEVENSON
Grain Creek
MT. BREW
North Arm
CARIBOO REGION
Tasse Lake
QUESNEL LAKE

FIGURE 1. Location of the Cariboo Lake study areas.

2.1 Study Area

The summer-harvested cutblock was in a moist subzone of the Engelmann Spruce-Subalpine Fir Biogeoclimatic Zone (ESSF) which, on the lowest elevations, phased into the Interior Cedar Hemlock Zone (ICH). The block had a southerly aspect and ranged in elevation from 1200 to 1500 m. Lodgepole pine was the dominant tree species and was accompanied by Douglas-fir, Engelmann spruce and western redcedar. The winter cutblock was in the moist subzone of the ESSF. Lodgepole pine, Engelmann spruce and subalpine fir were the major tree species harvested.

After joint field consultations between the licensee and MoFL, Weldwood of Canada Ltd. prepared a logging plan incorporating both small crawler tractor and cable systems for a summer operation. The remainder of the summer-harvesting block consisted of sensitive site types (Orthic Humo-Ferric Podzols occurred on the shallow gravelly sandy loam to silt loam morainal and colluvial parent materials). Areas of irregular topography with bedrock-controlled landforms were designated for small crawler tractors, while smooth sloping topography with adequate deflection was designated for cable yarding. Cable systems were chosen for harvesting very sensitive sites characterized by steep, moist, loamy, morainal parent materials under Orthic Humo-Ferric Podzols. On the winter block the small tractors were used mainly on irregular topography, while cable yarding was used on the long, smooth, steep slopes.

3 METHODS

The study monitored soil disturbance by machine activity during logging operations. Cable and small crawler tractor logging systems were studied under summer and winter harvesting conditions.

Soil disturbance caused by machine activity was surveyed on the ground by direct measurement, and disturbed areas were categorized as truck road, landing or skidroad. Skidroads were stratified into three segments (main, branch and spur) based on relative frequency of use. (All areas travelled by machines, and all cutbanks and fill slopes, were included in the assessments.)

Disturbance criteria were initially developed for summer harvesting situations. The trial was expanded to include winter operations and disturbance criteria were changed. Winter skidroads were thought to be less damaging than summer skidroads because snow was used in their construction. Soil compaction data for summer and winter skid roads were collected to record some of the soil changes caused by machine activity and seasonal differences.

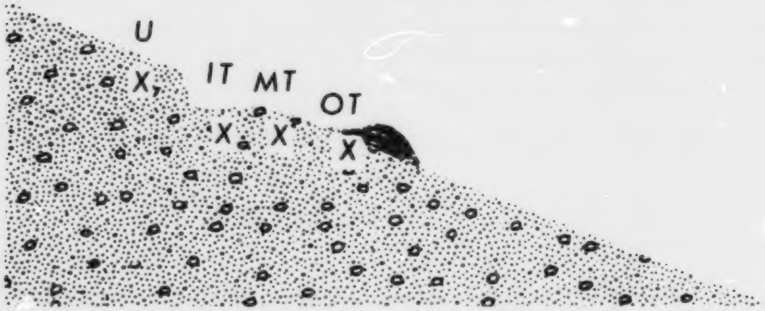
For summer operations, the detrimental soil disturbance measured included:

1) all bladed (mineral soil exposed) running surfaces from top of cut to outside of berm on truck and skidroads;
2) the surface area of landings;
3) the fill slope of truck roads; and
4) all running surfaces not included above.

For winter operations, the detrimental soil disturbance measured included:

1) the area in truck roads from top of cut to outside of fill by length;
2) the area of landings; and
3) the area of excavated mineral soil for skidroads.

Soil bulk density was measured on skidroad surfaces the summer following harvesting. For tractor yarding, samples were taken across the skidroad (Figure 2); for cable yarding, soil bulk density was sampled where logs had dragged across the surface and exposed mineral soil. The sample position for cable was considered analogous with the mid-road location of the tractor logging. Soil bulk density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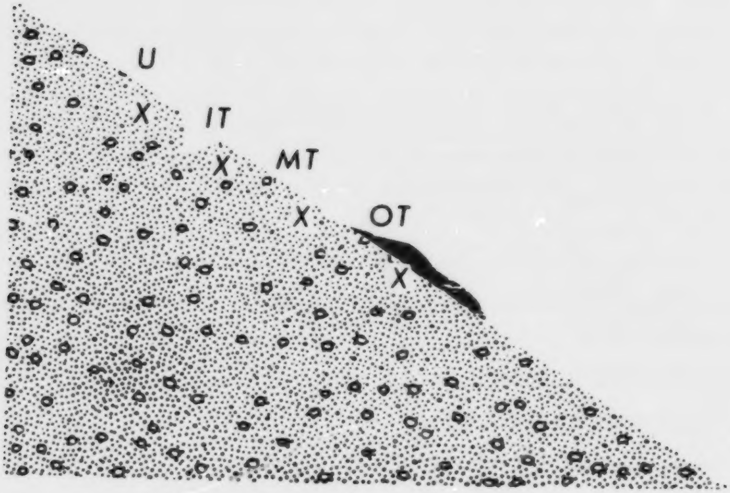
SUMMER SKIDROAD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WINTER SKIDROAD

FIGURE 2. Skidroad cross-section showing location of soil bulk density sample points (x) for summer and winter skidroads. U - undisturbed; IT - inner track; MT - mid-trail; OT - outer track.

samples of approximately 500 cm^3 were taken using the core method, and data are presented on the <2 mm soil fraction (see Table 3).

4 ANALYSIS

Detrimental soil disturbance survey data were compiled for each harvesting system/season combination and compared to the disturbance goals set prior to harvesting.

Soil compaction was evaluated from soil bulk density data statistically and technically. Analysis of variance, using Duncan's Multiple Range test (General Linear Model procedure of SAS) for unbalanced data sets, was done to test the soil bulk density means for each sample stratum by logging system and season. The technical evaluation used a preset increase of 15% in soil bulk density as an indication of detrimental soil compaction (Howes *et al.* 1983). The ratio of samples with detrimental soil compaction to total samples was used to indicate the extent of soil compaction impacts.

5 RESULTS

A total of 255 ha were logged during the five summer and three winter cable settings (65 and 18 ha, respectively), and 16 summer and 13 winter small crawler tractor settings (94 and 78 ha, respectively). Table 2 presents descriptive statistics for each system and season.

The survey results indicated that the maximum soil disturbance of 10% was met by the use of the cable system, and the soil disturbance from summer tractor logging was nearly double the set maximum level. The integration of logging systems likely increased the road density required for tractor logging and reduced the road density needed for cable compared to the independent application of the logging systems. However, because the two logging systems shared a common road network, it was not possible to compare road- and landing- related disturbance levels for each system.

The skidroad density of 259 m/ha in the summer increased to 286 m/ha in the winter, resulting in a 3.6% increase in skidroad disturbance for the winter tractor operations.

Analysis of variance results indicated significant increases ($p<.05$ in soil bulk density in some strata, relative to the mean undisturbed levels (see Table 3). The inner track position on skidroads showed significant increases in bulk density. None of the sample positions on the winter spur skidroad segments had a significant increase in soil bulk density.

A lower incidence of soil compaction on winter skidroads than on summer skidroads was assumed to reflect a lesser overall detrimental disturbance for winter skidroads. Summer skidroads were cut-and-fill constructed using surface woody debris and soil. Winter skidroads were constructed with a mixture of soil, woody debris and snow, which was left to freeze together prior to use. Only a small amount of soil was needed to create a serviceable winter skidroad. On slopes, the most common cross-section was a narrow mineral soil cut of 0.75-1.25 m. At the time of construction, the snow- covered soils were moist to wet and not frozen.

No significant increase ($p<.05$) in soil bulk density occurred on the most heavily disturbed cable yarding roads. The lack of direct machine activity on yarding roads reduces the number of loads that can cause physical soil damage. The spots where damage might have occurred were generally localized on small convex-shaped ridges.

TABLE 2. Site disturbance survey, Cariboo Lake logging trials[a]

		Area (%)						
					Yarding			
System	**Season**	**Roads**	**Landings**	**Roads & Landings**	**Main**	**Br.**	**Spur**	**Total**
Cable	Summer	-	-	10.1	-	-	-	10.1
	Winter	3.4	4.1	7.5	-	-	-	7.5
Small Crawler Tractor	Summer	7.7	4.2	11.9	0.6	3.7	3.4	19.6
	Winter	7.3	4.2	11.5	0.4	2.2	2.5	16.5

[a] % disturbance based on area occupied by cut, running surface and fill of main roads, surface plus cut area of landings, cut plus running surface of summer-built skidroads and cut area for winter-built skidroads.

TABLE 3. Analysis of variance of soil bulk density for skidroad segments[a]

Logging System		**Sample Location**			
Season		**Mean Soil Bulk Density[c](kg/m^3)**			
	Skidroad Segment	**IT[b]**	**MT[b]**	**OT[b]**	**U[b]**
Cable, Summer	Cable	–	960^{x}	—	850^{x}
Tractor, Summer	Main	1260^{x}	1150^{x}	1070^{xy}	920^{y}
	Branch	1170^{x}	1030^{xy}	990^{xy}	850^{y}
	Spur	1220^{x}	970^{y}	950^{y}	850^{y}
Tractor, Winter	Main	1270^{x}	1170^{xy}	1080^{y}	1070^{y}
	Branch	1350^{x}	1190^{y}	1080^{y}	1120^{y}
	Spur	1080^{x}	920^{x}	930^{x}	940^{x}

[a] Duncan's multiple range test using a general linear model for unbalanced data set.

[b] IT = inner track; MT = mid-trail, between tracks; OT = outer track; U = undisturbed control.

[c] Means with different superscripts on horizontal rows are significantly different at the $p<0.5$ level.

The mean undisturbed bulk density for the winter tractor operation (1050 kg/m^3) was significantly higher at the 5% probability level than for the summer cable (850 kg/m^3) and summer tractor (880 kg/m^3), based on Duncan's multiple range test. Because of their higher undisturbed bulk density, the soils on the winter tractor block may be more sensitive to damage from compaction than the soils on the summer block. Most soil compaction on winter trails probably occurred during trail building, as soils were moist and unfrozen at the time of construction.

The second analysis of the soil bulk density data, determining the frequency of samples having detrimental soil compaction based on a greater than 15% increase in bulk density, is presented in Table 4. Detrimental soil compaction was defined as a 15% increase in soil bulk density. The U.S. Forest Service uses a 15% increase as part of its regulations defining detrimental soil compaction (Howes *et al.* 1983). This technical criterion is used for comparing relative variation by season of logging and sample location.

The undisturbed sample means for each stratum were used as the data for the evaluation. Frequency of detrimental soil compaction is expressed as a percentage of all samples within each stratum. Overall frequency of detrimental compaction was 61% for summer skidroads and 32% for winter skidroads. The inner track sample locations more frequently had detrimental soil compaction than other sample locations. Detrimental soil compaction on the inner track is explained as a natural increase in soil bulk density with depth due to machine excavation and/or increases caused by machine activity on the soil.

Intensity of skidroad use and soil compaction appeared to have a direct relationship for the winter operations, whereas a similar trend for the summer operations was not indicated. Frozen mixtures of soil, woody debris and snow comprising the outer track position, and frozen soil at mid-road positions of winter skidroads were probably the reasons for reduced frequency of detrimental soil compaction on winter trails. This relationship supports the respective definitions of summer and winter detrimental soil disturbance for skidroads as used in this study.

TABLE 4. Proportion of soil bulk density samples with 15% + increase on tractor-logged skidroads[a]

Season	**Skidroad Trail Segment**	**Mean Undisturbed (kg/m^3)**	**IT[b] (%)**	**MT[b] (%)**	**OT[b] (%)**	**Segment Total %**
Summer	Main	920	71	64	50	62
	Branch	850	75	67	58	67
	Spur	850	85	38	38	54
	Type total	880	77	56	49	61
Winter	Main	1070	54	31	31	38
	Branch	1120	75	16	17	36
	Spur	940	22	22	0	17
	Type total	1050	53	24	19	32

[a] Howes *et al.* (1983) in part define detrimental soil compaction as a 15% or more increase in soil bulk density.

[b] IT = inner track; MT = mid-trail, between tracks; OT = outer track; U = undisturbed control.

6 DISCUSSION

Attempts to reduce detrimental site disturbance must focus on truck roads, landings and yarding disturbance, both individually and collectively (Froehlich and McNabb 1984). Road layout on variable and steep terrain is often difficult, and can be compounded when two or more logging systems are to be used within one block. Both harvesting systems in this trial shared the same road network, which provided similar site conditions for comparison of results, but also introduced a conflict with efficient road layout for each system independently. It also negated any road disturbance comparisons between systems.

The area committed to landings was high relative to levels found in other surveys (Table 1). Settings averaged 6 ha for both summer and winter ground skidding operations, with largest settings being 8.5-10 ha in size. Future operations could reduce the portion of the cutblock area devoted to landings by decreasing the number of landings.

Skidroad occupancy was the principal difference between ground and cable harvesting systems. The area occupied by skidroads in the small crawler tractor settings represents a major reduction over levels reported for conventional ground skidding systems. The narrow width of small crawler tractors allowed for narrower trails, which generally required minimal cuts and could be routed between trees, thus eliminating the need to remove stumps. Building trails along an angle of attack from upslope positions may also have resulted in shallower cuts. The shallow cut-and-fill running surface of summer skidroads was irregular in grade and had a distinct outslope which maintained natural surface drainage patterns. Fully bladed trails required the most aggressive water barring to control surface runoff.

Winter trails were generally in-sloped to prevent machines and logs from sliding off the trail surface. The use of snow as trail-building material resulted in less continuous displacement of mineral soil. Some "free skidding" without trails was attempted on the winter block, but the small machines could not productively cope with the stumps hidden in the deep, soft snow.

7 SUMMARY

The study indicated that, under favorable conditions, winter small crawler tractor operations could generate detrimental soil disturbance to levels that were more comparable to those produced in cable systems than in traditional conventional ground skidding operations. Merrill and Wagner Division realized a cost saving using the small tractors rather than cable yarding (J. Mansell, pers. comm., 1986). Small tractor harvesting was more capable of meeting set soil disturbance limits through well-planned and supervised operations on shallow, well-drained, coarse-textured soils on irregular 30-50% slopes for summer operations and on irregular 30-60% slopes with variable stable soils for winter operations. However, the cable systems were more capable of minimizing soil disturbance on the steep slopes regardless of season.

Different harvesting systems perform optimally under different conditions. Under winter conditions, small tractors reduced potential yarding-related detrimental soil disturbance compared to that which occurred under summer conditions. A small crawler tractor system can more effectively winter-log sites with a wider range of terrain and soil characteristics by using snow in trail building. Compared to winter operations, summer tractor harvesting will require sound planning and a narrower range of site and soil conditions to meet the disturbance levels applied in this study. Reducing skidroad density and increasing setting size are two factors that could lower disturbance levels. Soil compaction was less evident on winter skidroads than summer skidroads.

Some research trials would be valuable for assessing the productivity impact of soil compaction and the other soil alterations, and for defining site protection needs. Soil damage must be specifically correlated with tree growth to determine soil protection needs definitely.

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ROADS AND FOREST SITE PRODUCTIVITY

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ABSTRACT

Construction of forest roads initially removes anywhere from 1 to about 30% of the area from tree production. Forest regrowth is possible on the entire road prism on roads that are closed after timber harvest, but only on the cut-and-fill slopes on roads that are kept open. Site conditions are poorest on road cuts and on the cut portions of the road surface, and tree height growth is reduced at these locations. In contrast, tree height growth on fills is usually not reduced relative to that on slopes next to the road. Microclimate changes and the disposition of runoff excess from the road itself, plus any subsurface flow intercepted by the road, also affect site productivity on the slopes adjacent to the road. Considering the soil moisture regime, site conditions should be improved above and below outsloped roads but only above on insloped roads. Studies of tree growth above and below roads tend to support these postulated responses. Severe reduction in site productivity adjacent to roads does occur when construction raises water tables on the uphill side of the road and when landslides originate in the road and translate onto the slope below. Productivity losses tend to be considerably less than the percentage of area devoted to roads except, possibly, where off-road groundwater or landslide problems exist. Adverse effects tend to increase with road width and vary by biogeoclimatic regions.

1 INTRODUCTION

The effects of forest road construction on watershed function and associated downstream damages are a major concern to forest land managers and other interested parties in the Western United States. By far the greatest emphasis has been placed on the downstream effects of roads, including changes in streamflow rates (Ziemer 1981; King and Tennyson 1984), in channel morphology (Lyons and Beschta 1983), and especially in sedimentation (Megahan 1985). Aside from evaluating the area required for road construction, there has been little concern about the effects of roads on site productivity. This paper explores how roads might influence site productivity with respect to tree survival and growth rate.

In this discussion, a road is defined as a vehicle corridor built with the use of cut-and-fill construction operations. The road prism comprises the entire disturbed width including the road cut, the road surface (plus any additional widening for ditches, berms, etc.), and the road fill slope. The road prism may be balanced, where the material excavated at a given site is used to construct the fill embankment at that site, or may involve transport of excavated material to construct fill embankments at other locations. In either case, it is the cut-and-fill operation that distinguishes roads from most skid trails used in the timber harvest operation (Figure 1).

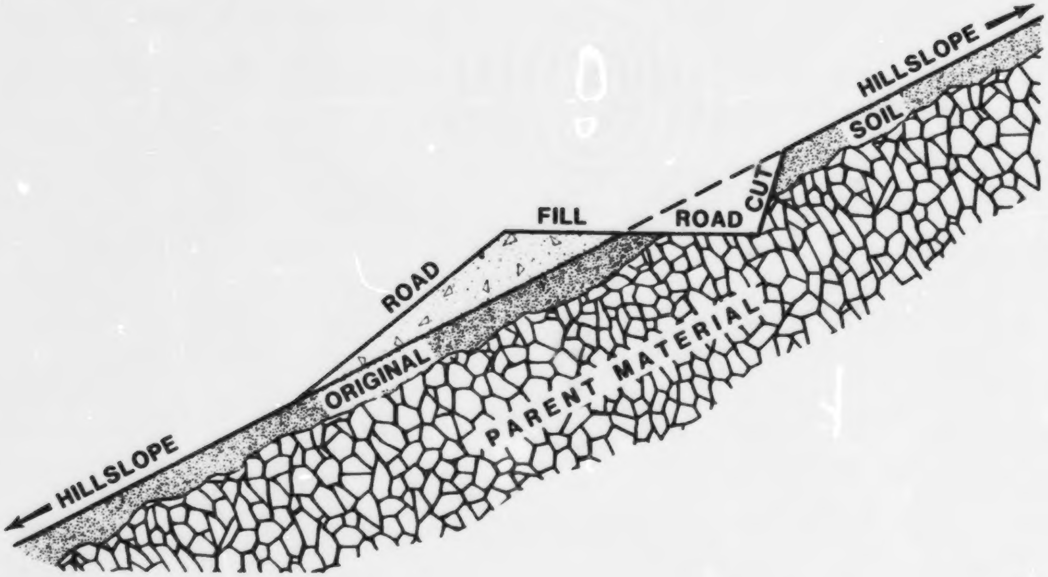

FIGURE 1. Example of cut-and-fill road construction on a mountain slope.

2 AMOUNT OF ROAD DISTURBANCE

The amount of land required for forest road construction is an important concern for evaluating effects on productivity. The area used obviously depends on individual road dimensions. The primary factors influencing the total area disturbed by road construction include the original fillslope gradient, the desired road width (including any additional widening for a ditch, berm, etc.), and the gradient of the cut-and-fill slopes (Fig. 1). Using these dimensions, the geometry of the entire road prism can be described (Megahan 1976).

The amount of road required for harvesting timber also varies with the type of timber harvest system used, because of differences required in road spacing and, in some cases, road width. The results of 11 studies documenting the area of road disturbance associated with alternative timber harvest systems are shown in Table 1. As might be expected, there is considerable variation in the percentages of the logged areas bared by road construction, ranging from 30 to 1%. Tractor logging averages the greatest at 11%, followed closely by ground cable operations (including jammer and high lead systems), averaging about 10%. At about 2%, road requirements are much less for skyline and helicopter systems. A common assumption is that the area devoted to road construction is lost from production. According to the data in Table 1, this appears to be true.

Consideration of the effects of road construction on site conditions can explain this loss. The influence that forest roads have on tree growth depends not only on the amount of land devoted to roads but also on whether the roads are allowed to remain open to traffic following timber harvest. If the roads are closed, the entire road prism is available for reforestation, subject only to the constraints imposed by the site properties of the road. However, it is often necessary to keep roads open after timber harvest for a variety of reasons, such as to serve as a part of the permanent forest access net, to provide access for fire suppression, or to accommodate future silvicultural operations. In this latter case, timber growth is possible only on the road cut-and-fill slopes, for as long as the road remains open.

TABLE 1. Soil disturbance from roads for alternative methods of timber harvest in the Western United States and Canada

	Percentage of Logged Area Bared				
Method of Harvest	**Roads**	**Skidroads and Landings**	**Total**	**Location**	**Reference**
Tractor					
Tractor - clearcut summer	30.0	---	30.0	British Columbia	Smith 1979
Tractor - clearcut winter	12.0	---	12.0	British Columbia	Smith 1979
Tractor - selection	2.7	5.7	8.4	California	Rice 1961
Tractor - selection	2.2	6.8	9.0	Idaho	Haupt & Kidd 1965
Tractor - group selection	1.0	6.7	7.7	Idaho	Haupt & Kidd 1965
Tractor - partial clearcut[a]	1.8	---	1.8	Idaho	King & Tennyson 1984
Tractor - partial clearcut	3.0	---	3.0	Idaho	King & Tennyson 1984
Tractor - partial clearcut	4.3	---	4.3	Idaho	King & Tennyson 1984
Tractor - selection	5.0	10.0	15.0	California	Ziemer 1981
Tractor & helicopter -fire salvage	4.5	0.4	4.9	Washington	Klock 1975
Tractor & cable -fire salvage	16.9	---	16.9	Washington	Klock 1975
Tractor - grapple summer	19.0	---	19.0	British Columbia	Smith 1979
Tractor - grapple winter	10.0	---	10.0	British Columbia	Smith 1979
Ground cable					
Jammer - group selection	25-30	---	25-30	Idaho	Megahan & Kidd 1972
Jammer - clearcut	8.0	---	8.0	British Columbia	Smith 1979
High lead - clearcut summer	9.0	---	9.0	British Columbia	Smith 1979
High lead - clearcut winter	6.0	---	6.0	British Columbia	Smith 1979
High lead - clearcut	6.2	3.6	9.8	Oregon	Silen & Gratkowski 1953
High lead - clearcut	3	1	4.0	Oregon	Brown & Krygier 1971
High lead - clearcut	6	1	7.0	Oregon	Brown & Krygier 1971
High lead - clearcut	6	---	6.0	Oregon	Fredriksen 1970

TABLE 1. (Continued) Soil disturbance from roads for alternative methods of timber harvest in the Western United States and Canada

Method of Harvest	**Percentage of Logged Area Bared** **Roads**	**Skidroads and Landings**	**Total**	**Location**	**Reference**
		Skyline and helicopter			
Skyline - clearcut	2.0	—	2.0	Oregon	Binkley 1965
Skyline - clearcut	1.0	—	1.0	British Columbia	Smith 1979
Skyline - partial clearcut[b]	3.9	—	3.9	Idaho	King & Tennyson 1984
Skyline - planned for partial clearcut	2.6	—	2.6	Idaho	King & Tennyson 1984
Skyline - planned for partial clearcut	3.7	—	3.7	Idaho	King & Tennyson 1984
Helicopter - clearcut	1.2	—	1.2	—	[c]

[a] Percentage watershed area in roads, approximately 16-34% of watershed clearcut.

[b] Percentage watershed area in roads, approximately 36-52% of watershed clearcut.

[c] Estimated by Virgil W. Binkley, Pacific Northwest Region, USDA Forest Service, Portland, OR.

3 SITE CHANGES WITHIN THE ROAD PRISM

A number of site factors can be influenced by road construction, including nutrient levels, infiltration rates, gas exchange rates, bulk density, rooting depths, moisture-holding capacities, shear forces (including snow shear), and microclimate changes in wind, solar radiation, snow accumulation, and temperature extremes (including frost effects). The degree of change in each site factor depends on location within the road prism. The harshest site conditions are found on the cut section of the road where original soil is removed, exposing subsoil or underlying parent material. On the road surface, adverse effects are greatest on the inside of the road because of excavation. Essentially, road fills are embankments made with material derived predominantly from lower soil horizons, subsoils, and underlying bedrock (Fig. 1). Such material is low in nutrients and, coupled with other adverse site conditions such as steeper slopes and more extreme microclimate conditions, might be expected to provide a poor site for vegetation growth compared to that on undisturbed slopes. The effects of traffic following construction causes additional adverse impacts because of compaction of the roadbed.

Smith and Wass (1985) reported a comprehensive study of site conditions on logging skid roads 17-23 years old in southeastern British Columbia. Site factors evaluated included bulk density, penetration resistance, total nitrogen, organic carbon, carbon/nitrogen ratio, acidity, free carbonates, coarse fragments, and temperature measured at a variety of depths. Samples were collected at eight locations: in the undisturbed slopes above and below the road, in the cut-and-fill slopes, on the road surface in the inner and outer tracks, in the center of the road, and on the road berm. In undisturbed soils, bulk density and pH increased with depth, while organic carbon, total nitrogen, and fine soil fraction decreased. This trend with depth was reflected by the samples collected in the cut sections of the road where bulk density and penetration resistance were high and organic matter and nitrogen contents were low. In contrast, bulk densities on the fill portions of skidroads were relatively low, and carbon and nitrogen levels were equal or (on a soil volume basis) exceeded the levels in the upper zones of undisturbed mineral soil. The study showed a slow rate of recovery of bulk density, penetrability, carbonate concentration, and pH, and large increases in organic carbon and total nitrogen in response to vegetation regrowth in the 17 to 23-year periods since logging.

4 TREE GROWTH WITHIN THE ROAD PRISM

In comparison to crop tree performance on slopes adjacent to roads, tree survival and growth on areas disturbed by road construction may increase because of reduced vegetative competition. In fact, cut-and-fill construction practices (called stripping or terracing) similar to those used for roads are often advocated to improve survival and growth of some tree species. For example, Hall and Curtis (1970) documented 29% greater survival and 59% greater height growth on 10-year-old ponderosa pine (*Pinus ponderosa* Laws.) planted on terraces constructed on granitic soils in Idaho. Unfortunately, construction of roads usually entails more extensive soil disturbance than does construction of terraces, and post-construction traffic further constrains tree growth. Thus, part of the potential increases in tree growth caused by reduced competition may be negated by adverse site effects, which are greatest in the cut sections of the road and often cause reduced tree growth compared to the fill sections of the road. These site differences are evident in the height growth of 11-year-old lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) planted on logging roads on granitic slopes in Idaho (Figure 2).

Smith and Wass (1979, 1980) conducted comprehensive studies of tree survival and growth on abandoned logging roads in southeastern British Columbia. They evaluated tree densities and growth on many of the same skidroads that were also evaluated for changes in site conditions (Smith and Wass 1985). The study roads were in both clearcut and wildfire areas ranging in age from 9 to 22 years. Data were collected on five species, including Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and western larch (*Larix occidentalis* Nutt.). Tree densities were lower on the skidroads, probably because of reduced seed availability and the initially harsh environment with respect to seedling establishment. Similar to the response illustrated in Fig. 2, tree growth was consistently less on the cut portions of the road prism than on the fill portions of the roads.

FIGURE 2. Growth of 11-year-old lodgepole pine on cut-and-fill portions of a jammer road constructed from granitic materials in Idaho. Photograph courtesy of Robert Steele, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Boise, ID.

Megahan (1974) documented the effects of reduced nutrient status on road fills constructed from coarse-textured, granitic materials in the Idaho batholith. Following treatment with 28-5-0 fertilizer in tablet form, planted ponderosa pine height growth was increased 32-116% depending on the year of planting and the time since planting. Fertilization effects were greatest the second year after treatment and decreased rapidly in the following 1 or 2 years. Amelioration of soil microclimate conditions was also suggested by the increased growth on plots treated with straw mulch.

Placement of fill material on-site may minimize or even mitigate the adverse effects of lowered nutrient levels and severe microclimate by improving other site factors such as increased depth for rooting, reduced resistance to root penetration, and greater total moisture-holding capacity. This was the case for most of the areas sampled by Smith and Wass (1979, 1980) in British Columbia. Except for one site, there were no statistically significant reductions (95% level) in mean tree height growths on the outer disturbed (fill) portions of roads, compared to slopes above and below the roads. Smith and Wass were also able to evaluate the net effect of tree growth within the entire road prism. At an assumed value of 32.3% for the area occupied by skidroads, there was a net change in tree growth on all sampled roads, ranging from a decrease of 14.8% to an increase of 21.9%, compared to adjacent clearcut or burned slopes.

5 SITE CHANGES ADJACENT TO ROADS

Roads affect site productivity outside the road prism primarily by changing the hydrologic function of the hill slope under both saturated and unsaturated flow conditions. Saturated subsurface flow is a common occurrence on many forested slopes in mountainous areas. Water easily infiltrates permeable surface soils and tends to concentrate at depth as hydraulic conductivities decrease. Downslope flow then occurs along the zone of reduced hydraulic conductivity. Conditions conducive to subsurface flow include (1) a slope gradient, (2) permeable upper horizons, (3) a zone of reduced hydraulic conductivity, and (4) a large enough volume of water to cause saturation from either large storm events or snowmelt, or both.

On steeper slopes, road construction intercepts the subsurface flow layer. Water then emerges on the road cut, causing rapid overland flow. If the roadbed is outsloped, the intercepted water runs across the road and generally reinfiltrates on the downhill side of the road. Many times, however, the intercepted water does not flow uniformly across outsloped roads, but rather is concentrated in traffic tracks or ruts on the surface before returning to the slope below the road. Thus, saturated flows are decreased in some portions of the slope following road construction and increased in others. Similar effects occur on insloped roads, only in this case the intercepted water is carried in the road ditch to a nearby culvert before being dumped into a nearby channel or onto the slope below the road. In either case, there can be large increases or decreases in the moisture content below roads, which may influence tree growth.

Megahan (1983) measured subsurface flow interception by roads constructed on steep, granitic slopes in Idaho. Prior to logging, the total volume of water intercepted by the roads averaged about 35% of the total runoff for perennial study watersheds in the vicinity. This runoff is estimated to be 7 times the amount of accelerated, direct runoff from roads, which is caused by precipitation (both rain and snowmelt) falling directly on the road. After the occurrence of logging and wildfire on the slope above the road, reduced evapotranspiration and increased snow accumulation and snowmelt rates caused greater piezometric storage and increased volumes and rates of intercepted subsurface water outflow. Volumes of flow were increased about 100% and were accompanied by peak flow increases of about 30%. Post-logging subsurface flow intercepted by the road was estimated to exceed direct road runoff by a factor of 18. Such increases in sub-surface flow can further magnify the possibility for changes in site productivity adjacent to the road.

Roads also modify the unsaturated soil moisture regime of slopes, which can lead to changes in site properties adjacent to the road. During unsaturated flow, water still tends to have a net downhill flow vector, although it cannot emerge on the road cut as does saturated subsurface flow, because of negative pore pressures in the soil. Accordingly, relative soil moisture contents above the road cut should gradually increase over time as the slope drains, compared to that on sites further upslope. Likewise, unsaturated soil moisture contents should be relatively higher below roads at the point of discharge of road runoff compared to locations farther downslope. Vegetation removal during road construction may also tend to increase post-construction soil moisture levels adjacent to the road because of reduced interception and transpiration losses of water.

I am unaware of any studies that use modern sensing equipment to specifically test the effects of roads on the unsaturated soil moisture regime. However, we have some old data in our files collected on granitic slopes of the Idaho batholith, which shed some light on the question.[1] Soil moisture was measured with a King tube core sampler and was expressed as percentage by weight. Over the summer, successive transects were sampled downslope between three outsloped, jammer logging roads to evaluate time trends in soil moisture contents. The study site had a slope gradient of 60% and had been logged prior to the measurements being made.

The data are summarized in Fig. 3. Each data point shown represents the average soil moisture for 15 cm depth increments, from 15 to a maximum of 137 cm. A star adjacent to a point on a given sample date indicates statistically significant differences (95% confidence level) between one or more locations on the same transect. The data suggest that road runoff tends to result in high soil moisture contents in the slopes immediately below the outsloped roads, especially below the second road. As indicated by our old data, water tends to accumulate downslope, above the road cut as the slope dries out during the summer. The point of maximum water content is upslope about 2 to 6 m above the road cut, with lower amounts at the road cut face in response to evaporation gradients at the surface. Although hardly conclusive evidence, these data do suggest a relatively favorable moisture status above and below outsloped roads at a high moisture stress time of the year. If such trends are common, then tree growth may be enhanced adjacent to roads, especially in areas with drier climates.

6 TREE GROWTH ADJACENT TO ROADS

With the potential for increased unsaturated soil moisture levels next to outsloped roads, and the possible microclimate effects such as greater light on the roadside of forest stands, one might expect increased growth of vegetation adjacent to an outsloped road. A study by Pfister (1969) reported such a response on 40-year-old white pine plantations in northern Idaho, on soils derived from metamorphic rocks of the "Belt Series." Because all roads included in the study were single lane, outsloped, and part of the active transportation system, no tree growth occurred on the road surfaces. Diameter and height growth were greater for trees adjacent to the roads than for trees farther in the stand, with the largest effects occurring in trees below the roads. On average, growth of trees within the first 7 m from the road averaged 30% higher than that for trees farther from the road, with the largest acceleration of growth occurring immediately below the road. The increased volume produced in the roadside zone was sufficient to compensate for reduced growth on 4 m of the overall road width of 5.6 m, so there was only 1.6 m of unproductive road width. Pfister (1969) attributed the increased growth to reduced competition following road clearing. However, our data showing a tendency for increased soil moisture above and below roads suggest an additional vehicle for increasing growth rates.

Our unsaturated soil moisture data and the results of Pfister's (1969) study suggest the possibility of increased growth of trees above and below outsloped roads. Insloping or ineffective outsloping might reverse the growth pattern below roads, especially where subsurface flow interception is large. In this case, intercepted subsurface flow and runoff from the road itself are prevented from re-entering the slope below the road, thus reducing late-season soil moisture levels. We do not have any experimental data to test this hypothesis specifically. However, Smith and Wass (1980) did evaluate growth patterns of lodgepole pine and Douglas-fir above and below insloped roads compared to adjacent locations without roads. All three test sites were located in a large, 19-year-old burn that had been salvage-logged. As indi-

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[1] W.J. Kidd, unpublished data, U.S. Department of Agriculture, Forest Science, Intermountain Research Station, Boise, ID.

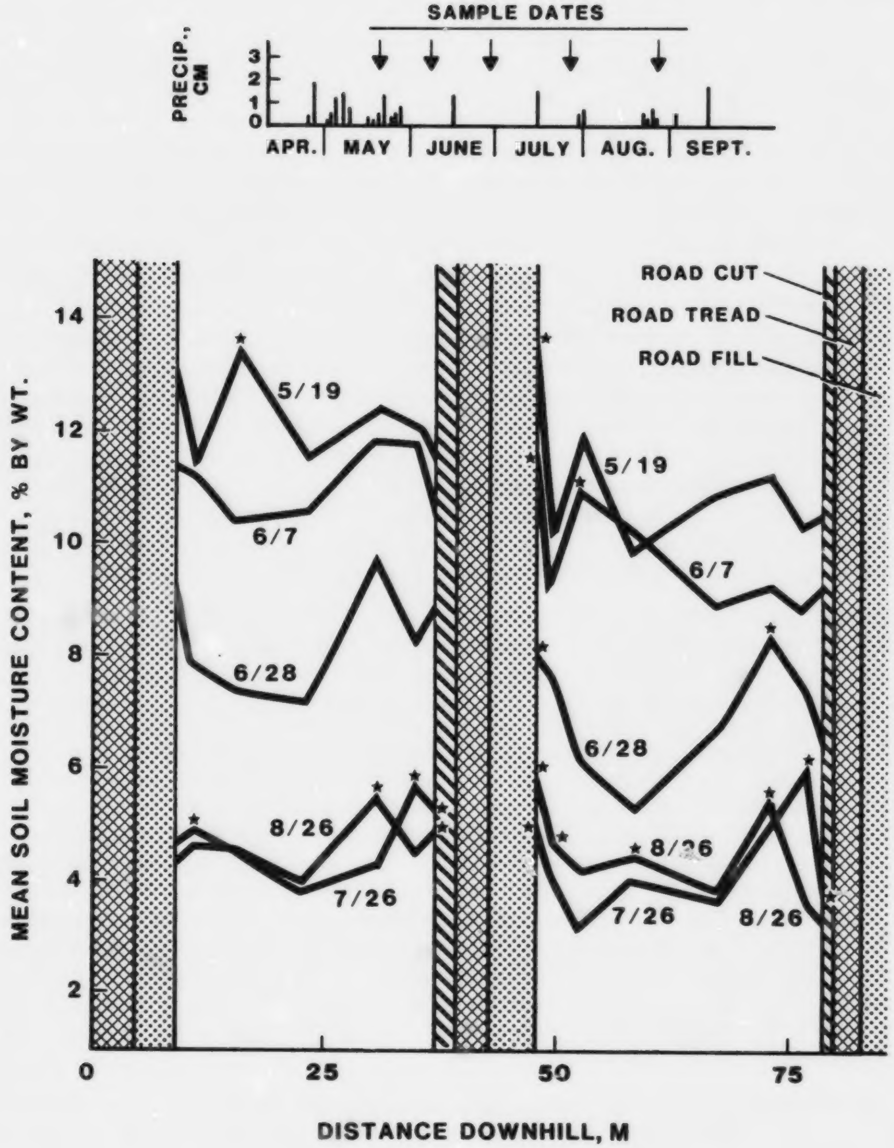

FIGURE 3. Changes in unsaturated soil moisture levels between logging roads on a cutover, granitic slope in Idaho. A * indicates statistically significant differences (95% confidence level) between one or more locations on the same transect.

cated by the mean height of the tallest trees, the data showed the same trends as hypothesized above, at all three test sites: trees above the roads consistently averaged taller than in adjacent areas without roads, and trees below the roads consistently averaged shorter. However, differences were statistically significant at the 95% level in only one instance where the mean height of the tallest trees below the road was reduced 23% for lodgepole pine and 20% for Douglas-fir.

7 OTHER FACTORS AFFECTING TREE GROWTH NEAR ROADS

Both surface and mass erosion tend to increase following road construction in response to such factors as removal of vegetative cover, interception of subsurface flow zones, increased overland flow, and increased slope gradients on cut-and-fill slopes. Many times, accelerated erosion on the road also accelerates erosion on the slope below, which leads to site damage. Downslope damage is almost exclusively associated with mass erosion when a landslide originates within the road and causes scour in the slope below the road.

In the Pacific Northwest, the problem is quite widespread because road construction is by far the most common cause of landslides in unstable forested areas. For example, Swanson *et al.* (1981) summarized the results of a number of studies in the Mapleton area of Oregon and reported slide frequencies averaging 140 times greater per unit area of roads compared to that on undisturbed slopes. Clearcutting increased slide frequency only an average of 7 times. Compared to cutting units, roads usually occupy only a small percentage of the area involved in timber harvesting so that unit area rates can be misleading. Ice (1985) summarized the results of 13 studies in the Northwest United States and Canada where landslide frequencies were weighted by the area of land occupied by roads and cutting units. On average, about 62% of the management-induced landslide erosion was caused by road construction.

Data were collected in the Clearwater River basin of Idaho in 1974[2] to document the amount of downslope damage caused by landslides originating on forest roads. The area of the landslide scar within the road prism was recorded for each slide, as well as the area of any landslide scars below each road. Downslope damage was found on 58% of the 88 slides sampled. At 0.12 ha per slide, significantly greater damage (95% level) occurred below the roads as compared to the average area of 0.043 ha per slide within roads. Thus, about 74% of the damage from road-associated landslides actually occurred on the slopes below the roads.

Putting the overall effects of road-induced erosion on site productivity into perspective, we find that the proportion of forest area that is involved in landslides in the Pacific Northwest is generally less than 1% (Ice 1985). Burroughs (1985) reported that unstable soils exist on about 1098000 ha of National Forest lands in Oregon and Washington. Based on a 1% figure, and assuming the above-cited percentages of 62, 58, and 74 apply, the off-road site damage from road-induced landslides generally amounts to less than 0.3% of the total area. For National Forest lands in Oregon and Washington, this amounts to less than 3300 ha. Duration of reduced productivity on these sites varies greatly, ranging from 10 to 15 years on moist sites in the Pacific Northwest (Ice 1985), to over 85 years in the Queen Charlotte Islands of British Columbia (Smith *et al.* 1986).

Forest road construction can also affect site productivity outside the road prism by raising groundwater levels. This occurs when fill placement inhibits groundwater flow, causing water tables on the upslope side of the road to rise. The resulting flooding kills trees growing in the area, and the site remains unproductive for trees for as long as the flooding problem persists (Stoeckeler 1965; Boelter and Close 1974). Normally, proper road drainage design eliminates such problems. However, lack of removal of underlying organic layers before placement of fill material, and omission or improper placement of drainage ditches or culverts can inhibit groundwater movement (Stoeckeler 1967). Problems of this type are most common in relatively flat areas with highly organic soils, such as occur in parts of the central

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[2] Unpublished data, U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Boise, ID.

United States and Canada, but they can occur in mountain meadow areas as well. Stoeckeler (1967) found impaired productivity on an estimated 12 000 ha of forest land in northern Minnesota, caused by poor road construction practices that increased groundwater levels.

One additional effect of roads may occur. We know that nocturnal cold air drainage is an important component of the microclimate, especially in mountainous areas. Geiger (1957) illustrates the cold air ponding caused by obstructions such as a railroad grade. Roadfills can cause similar cold air ponding compared to pre-road conditions and may reduce productivity on the uphill side of the road. There is no question that road construction causes localized cold air ponding, especially in mountainous areas. However, I was unable to locate any references documenting effects on tree growth.

8 CONCLUSIONS

Construction of roads for timber harvest initially removes anywhere from 1 to about 30% of the total forest area from tree production, depending on road design standards and the type of timber harvest system. However, forest regrowth following timber harvest compensates for initial productivity losses so that the ultimate loss of productivity tends to be considerably less than that suggested by the percentage of area devoted to roads. The amount of forest regrowth depends on whether the road is closed to traffic, and on site conditions within and adjacent to the road.

Within the road prism, the most adverse site conditions are found on road cuts and on the cut portions of the road surface, and tree height growth is reduced at these locations. Increases in rooting depths, ease of root penetration, and total moisture-holding capacity in fill portions of the road tend to compensate for other unfavorable site conditions so that tree height growth in fills is usually not reduced — and may be increased — compared to that of trees on slopes next to the road.

Roads also affect site productivity on the slopes adjacent to the road prism. Some possible causal factors include changes in microclimate, such as increased light, the disposition of runoff excess from the road itself, plus any subsurface flow intercepted by the road; and changes in the unsaturated soil moisture regime. The nature of the road drainage design is an important factor regulating moisture responses.

In some situations, severe damage to site productivity adjacent to roads does occur when road construction raises water tables to critical levels on the uphill side of the road, and when landslides originate in the road and are manifested on the slope below. Site productivity remains permanently impaired in cases where water tables are raised, unless remedial road drainage practices are used. The duration of reduced productivity on slide scars ranges from about 10 to 80 years, depending on location.

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SESSION 1-2 ROADS

LOGGING ROADS: LANDSCAPE MANAGEMENT IMPLICATIONS OF SOIL DISTURBANCE AND EROSION

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ABSTRACT

Conflicts between timber extraction and other uses of the forest have become more frequent in British Columbia. From a political standpoint public support is increasingly important in our ability to implement sound forest management. The public often lacks the technical expertise to judge whether sound forest management practices are being implemented. The "appearance" of the forest is extremely important in the public's perception of the quality of forest management taking place. Therefore, landscape management, aimed at retaining and enhancing the scenic value of our forests, must be an integral part of forest management in British Columbia.

Logging road construction is one aspect of forest management that has a strong effect on the scenic quality of forests. Cutbanks, over-cast material (material pushed from the roadbed down the slope during road construction) and soil erosion are activities that affect the visual environment and are associated with road construction on the forested landscape of Western North America.

This paper examines the visual impact of typical logging road construction, and describes current landscape management policies and practices of the B.C. Ministry of Forests and Lands. The role of soil disturbance and erosion in contributing to visual impact is examined, and recommendations are made for minimizing the visual impact of logging roads.

1 INTRODUCTION

"Forest landscape management" includes the consideration of scenic values as one of the factors in forest management decisions. Significant strides have been made in gaining acceptance for landscape management, but it is still not well understood by many within government and the forest industry. In fact, there are many misconceptions about forest landscape management.

The purposes of this paper are:

a. to clarify some of the common misconceptions about forest landscape management,

b. to examine the relationship between soil management and landscape management, particularly as they relate to soil disturbance in the construction of logging roads, and

c. to identify management practices that will reduce the visual impact of logging roads.

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Only in relatively recent times has landscape management achieved official status within the B.C. Ministry of Forests.[2] The impetus for the forest landscape management program in British Columbia was largely a response to growing public concern over deteriorating visual landscapes. The public today is more environmentally aware, more mobile, and, thus, more likely to come into contact with manipulated forest landscapes and less willing to accept the word of the "expert" that proper management is being applied. At the same time, the public does not have the technical expertise to evaluate forest management activities adequately and are likely to base judgments of the quality of management on "how it looks." We need the wood, fiber, forage and minerals from our forests. The use of the forest for these purposes can be halted or delayed by public concern. Therefore, it is imperative that landscape management be considered a part of forest planning and management, as a means of both assuring the public that good management is occurring and avoiding delays.

Soil scientists are concerned about erosion, soil disturbance, loss of topsoil and loss of soil productivity in the forest. All of these affect the appearance and scenic value of the forest landscape. Many forest management practices beneficial to forest soils also benefit landscape management.

This paper is divided into three major sections. The first provides background information on landscape perception or "things" that are important in people's perception of landscapes. The second section examines the visual characteristics of logging roads, and the relationship between soil disturbance and visual impact. The last section discusses management implications for reducing the visual impacts of logging roads.[3]

2 LANDSCAPE PERCEPTION

Before the visual impacts of forest roads are discussed, it is important to have some understanding of how people perceive the landscape and of the factors important in their preference for different landscapes. First, a common misconception related to the nature of landscape preferences will be examined. This will be followed by a discussion of research relevant to landscape preference and logging roads; and, last, some conclusions on the influence of logging roads on landscape preference will be presented.

2.1 A Spurious Phenomenon

"Beauty is in the eye of the beholder." Or is it? This old adage has helped promulgate a misconception that has been harmful to the widespread acceptance of landscape preference. Certainly, there are differences in people's perception of landscape. However, landscape preferences are similar to many other human characteristics, such as size or facial appearance. We have little difficulty accepting the statement that, "people come in different sizes," or that, "each person looks different." However, if people come in so many different sizes, why do we marvel at the size of a football player nicknamed "The Refrigerator" or stare in disbelief at a basketball player who is 2.3 m (7 feet 6 inches) tall. If each person looks different, why do we not have to look twice to distinguish a human from a chimpanzee. Clearly, in spite of the differences we have some definite expectations that people are also similar, at least within certain ranges. Empirical research suggests we should have similar expectations with respect to landscape preferences. While individuals differ in their preference for landscapes, this variation often occurs within ranges or limits and, collectively, there are definite patterns to people's landscape preferences.

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[2] In the B.C. Ministry of Forests and Lands, the forest landscape management program was begun in 1978. The "Forest Landscape Handbook" was published in 1981 and the "Forest Landscape Management Policy" was established in 1982.

[3] The focus of this paper is on the visual impact of logging roads as part of a larger landscape or "how it would appear from a distance," because this is how most logging roads are experienced by the public. It is not the intent of this paper to examine the more detailed visual experience of someone who is actually on the logging road.

Empirical research into landscape preference has found a great deal of agreement on landscapes that people like and dislike (Shafer *et al.* 1969; Zube *et al.* 1974; Kaplan and Kaplan 1982; Williamson and Chalmers 1982; Miller 1984). This should not be surprising considering the importance of the visual sense to the human animal and the probable role of landscape perception in human evolution.[4]

2.2 Landscape Content

People react to the landscape in two ways. They react to the "content" of the landscape, or what the landscape contains; and they also react to how the landscape is organized or arranged (Kaplan and Kaplan 1982). In terms of landscape content, we know that people react positively to trees as a content and generally prefer what they perceive to be "natural" landscapes[5] over those that contain evidence of human occupation (Wohlwill and Heft 1977; Wohlwill and Harris 1980; Kaplan 1983). My research has shown "clearcutting" and "roads" to be landscape contents that have a negative influence on people's preference for shorelines in British Columbia (Miller 1984).

From a cognitive standpoint it is doubtful that people make a clear distinction in their minds between a landscape they think is beautiful and one with which they may associate other meanings. In other words, if they associate negative implications to a certain landscape content, they are not likely to find that landscape very scenic. For example, if a landscape contains a "content" that people perceive as being bad for the environment or bad for people — say some form of pollution — then it is likely to negatively influence their scenic preference for that landscape. This at least partly explains the negative reaction to clearcutting as a landscape content. Much of what people read or hear about timber harvesting in the popular media has negative connotations.

2.3 Conclusion

Based on the above discussion, the following conclusions can be drawn:

a. As a form of man-made alteration of the natural environment, logging roads can be expected to have a negative influence on people's landscape preference.

b. Empirical research has found other types of roads and clearcutting to be landscape contents that have a negative effect on landscape preference. It would be safe to assume that logging roads are a "content" that would also have a negative effect on landscape preference.

c. Logging road construction practices that result in visually apparent erosion and mass wastage will reinforce negative connotations related to timber harvesting, and will negatively influence people's landscape preference.

3 VISUAL CHARACTERISTICS OF LOGGING ROADS

In order to address management practices that can minimize the visual impact of logging roads, it is necessary to understand the visual characteristics of logging roads. These characteristics are influenced by forest management practices that visually impact the landscape.

First, some basic landscape management terms and concepts will be introduced. This will be followed by a discussion of the relationship between logging road construction and visual impact.

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[4] For a further discussion of the role of landscape perception in human evolution see "Cognition and Environment: Functioning in an Uncertain World" by Kaplan and Kaplan (1982).

[5] Natural landscapes should not be confused with wilderness landscapes. Natural landscapes may have been altered by man, but lack evidence of man's occupation, such as buildings and roads. In this context a second-growth forest or urban park would be perceived as "natural landscape" if it lacked evidence of man's occupation.

Based on the discussion of "landscape contents," or items contained in the landscape which influence people's preference for landscapes, several points are important with respect to the visual impact of logging roads. These are:

a. People prefer "natural" landscapes. Therefore, logging roads which appear to be more of a departure from the natural landscape will have greater visual impact;

b. Logging roads are likely to be a landscape content that have a negative influence on people's landscape preference. Therefore, hiding or making logging roads less easy to recognize is apt to be a good strategy for reducing visual impact; and

c. There are often negative connotations associated with timber harvesting. Therefore, logging roads that minimize visual evidence of erosion and mass wastage are likely to minimize these negative connotations and have a less visual impact.

3.1 Contrast

"Contrast" is a useful notion for assessing the degree of visual impact. Contrast is the degree to which alterations stand out visually or do not blend with the natural landscape. The greater the contrast between a logging road and the natural landscape, the more it will appear to be a departure from the natural landscape and the more easily it will be recognized and associated with timber harvesting, thus, causing greater visual impact. An obvious objective of landscape management is to assess the potential contrast of proposed landscape alterations and to recommend measures to reduce that contrast. Landscape elements and dominant line drawings are analytic tools used for this purpose.

3.2 Landscape Elements

Useful tools in describing the landscape are the "landscape elements": line, form, colour and texture. These are components of the visual landscape. Any landscape[6] can be described in terms of its line, form, colour and texture. Landscape alterations can also be described in terms of landscape elements. A logging road, for example, adds new line, form, colour and texture to the landscape. These added landscape elements may blend or contrast with the landscape elements of the natural landscape. As indicated above, the greater the visual contrast of a logging road, the greater its visual impact is likely to be. In general, alterations that repeat existing patterns in the natural landscape, such as repetitious lines, forms of a particular shape or size, and patterns of colours and texture, will contrast less (see Figure 1) with the natural landscape.[7]

3.3 Dominant Landscape Elements

Many natural landscapes are a complex myriad of landscape elements. Trying to decide whether an alteration contrasts or blends can be difficult. Not all landscape elements within a given landscape are of equal visual importance. Certain lines, forms, colours or textures may be more visually apparent than others, and are referred to as the "dominant landscape elements." To minimize the contrast of man-made alterations it is more important that alterations blend with the dominant elements rather than with other visual elements in the landscape. A dominant line drawing[8] is one means of assessing contrast with the dominant lines of a landscape.

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[6] While any landscape can be described in terms of line, form, colour and texture, the concept is most useful when applied to natural landscapes viewed from a distance.

[7] Note, the assumption here is that we are dealing with a primarily natural landscape and that the alteration will detract from the natural character and not be a landscape content to which people react positively.

[8] In order to assess landscape contrast it is necessary to identify viewpoints that are representative of how the site would be viewed by the public. This selection would be based on the number of viewers, what they are doing (e.g., commuting, camping, or hiking) and the view duration. For further discussion of viewpoint selection see B.C. Ministry of Forests (1981) or Litton (1973).

FIGURE 1. Increased visual impact caused by skidder trails that do not repeat natural lines and patterns of the landscape.

FIGURE 2. Contrast between linear form and colour of road and dominant line, colour and texture of natural landscape.

These limitations almost always cause logging roads to appear as nearly horizontal, relatively straight, linear elements in the landscape (see Figure 2). This is often in sharp contrast to the dominant natural lines of the landscape. The likelihood of strong visual contrast and visual impact is great.

3.6 Logging Roads, Soil Disturbance and Visual Impact

Much of the visual impact of logging roads and many of the measures for mitigating visual impacts are related to soil disturbance. Soil disturbance caused by road construction is often the primary source of "contrast" between the road and natural landscape. Disturbed soils or parent material often contrast sharply with the dominant colour and texture of the natural landscape. This contrast reinforces the unnatural linearity of the road as a landscape feature.

Soil disturbance and subsequent loss of productivity on road cutbanks and fill areas are a source of long-term visual impact. Long after the contrast between a clearcut and the surrounding natural landscape has begun to decrease as a result of green-up, the disturbed areas associated with a logging road continue to be a source of visual contrast.

This situation can be exacerbated further when road construction occurs on steep slopes or erosive soils. Logging roads built on steeper slopes are likely to be more visible from the surrounding landscape and will necessitate more soil disturbance in terms of larger cutbanks and fill areas. Erosion is likely to be more of a problem on steeper slopes because of the increased volume and velocity of runoff. Erosion and landslides can increase the size, as well as the visual contrast, of disturbed areas, making the road not only more visible, but reinforcing negative connotations of timber harvesting in the minds of viewers. Erosion and landslides can significantly lengthen the time required for green-up of disturbed areas.

Logging road construction practices also have an influence on visual impact. "Side casting," or the bulldozing of overburden material downslope from the roadbed, can be a source of significant visual impact. On steeper slopes it can result in long flows of disturbed soil and parent material, extending downslope at right angles from the road for a considerable distance. These flows create lines that are in sharp contrast to the natural landscape. The colour and texture of these flows also tend to contrast with those of the natural landscape and may never green-up in a timeframe meaningful to people. In addition, side casting can damage downslope vegetation, which can often play a useful role in screening the road from view and stabilizing the slope.

Logging roads are a significant source of visual impact in the managed forest. Soil disturbance associated with logging road construction is an important factor contributing to the visual impact of logging roads.

4 MANAGEMENT IMPLICATIONS

There are a number of measures that can be included in sound forest management, which will reduce the visual impact of logging roads. These measures fall into two broad categories: those related to the planning and layout of logging roads, and those associated with the construction of logging roads. They will be discussed in this order.

4.1 Implications for Planning and Layout

Planning and layout measures for mitigating the visual impact of logging roads are as follows:

a. When possible, logging roads should be located where they will be least visually evident from important viewing areas such as roads and recreation areas.

b. Logging roads should avoid steep slopes and erosive soils.

c. Logging road design standards should respond to specific site conditions. For example, on steeper slopes, minimum width requirements and the frequency of required pull-outs should be reduced.

d. When steep slopes and erosive soils are unavoidable, other means of accessing the timber, such as helicopter logging and balloon logging, should be explored for feasibility.

e. On steeper sites, yarding techniques that require skidder trails should be avoided.

f. Large cutbanks should be identified during the planning phase and revegetation and stabilization plans should be developed.

g. Areas for the disposal of overburden should be identified during the planning phase.

4.2 Implications for Construction

Mitigating measures important during site construction are as follows:

a. When overburden must be removed from the bed of the logging road, it should not be cast over the side, but end-hauled and disposed of in less visually apparent areas.

b. Visual management concerns should be explained to workers involved in constructing a logging road.

c. When blasting is necessary for the construction of a logging road, it should be done in a manner that minimizes the amount of material blasted over the edge of the roadbed and downslope, thus minimizing disturbance and visual contrast.

d. Care should be taken to minimize damage to adjacent vegetation, which can screen views of the road from the surrounding landscape.

e. Revegetation and slope stabilization should be given equal status with other phases of the construction process.

f. Disturbed areas should be vegetated as soon as possible to speed green-up and reduce contrast between the road and the surrounding landscape.

g. Unstable and erosive slopes should be stabilized through the use of mulch, seeding and structural devices to avoid the visual impact of erosion and landslides.

h. Landings and sorting areas should be kept as small as is functionally possible, and located preferably on flatter sites of lower visibility.

i. When cutbanks or rock cuts are not suitable for easy revegetation, the application of a colouring agent, such as coloured, fibrous mulch or an asphaltic emulsion, should be considered.

4.3 Conclusion

It is clear that with a little forethought and planning, and by following some reasonable guidelines during layout and construction, the visual impacts of logging roads can be greatly reduced. It is also clear that many of the mitigating measures for reducing visual impacts are also sound procedures from the standpoint of soil management and land stewardship.

Significant strides have been made in forest landscape management in British Columbia. However, it is still looked upon by many as a frill or an extra hurdle that foresters must clear in order to accomplish their real mission. This image must change: forest landscape management is not something separate from forestry. It is part of good forestry, just as a concern for the forest soil is a part of good forestry. Much of the public concern over forest harvesting today is the result of past poor forest management. We recognize this in our concern for restocking forest lands and increasing forest productivity. We must also recognize it by a concern for how our management activities, such as logging roads, affect the appearance of the forest.

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SESSION 1-3 FOREST SITE PREPARATION

SOIL DEGRADATION ASSOCIATED WITH FOREST SITE PREPARATION

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ABSTRACT

Mechanical site preparation may damage soil structure, leading to impairment of drainage and aeration. When severe compaction occurs, root penetration and available water retention may be impeded. Scalping of surface horizons may also be detrimental to nutrition. Slashburning sometimes results in deterioration of the nitrogen, copper and iron status of trees. However, some kinds of mechanical site preparation improve soil physical properties, slashburning sometimes benefits nutrition, and soil temperature regime is often improved by either burning or mechanical treatment. The implications of soil degradation can be obscured by positive effects of site preparation on tree survival and growth. The balance between positive and negative effects of site preparation on soils varies between sites. Several effects of site preparation are presumably temporary; the persistence of degrading effects is a topic requiring research.

1 INTRODUCTION

Site preparation is carried out to facilitate planting and to improve the establishment and early growth of seedlings. The research literature over the past decade indicates increased interest in site preparation impacts, but much remains to be learned about the possible soil degradation involved. It is relatively easy to measure a change in a soil property; it can be more difficult to prove that it represents degradation. Insofar as a change tends to result in reduced productivity, it may be considered degradation. However, when we look at seedling performance, we are looking at the net effect, that is, positive minus negative effects. So long as site preparation has a net positive effect, the individual negative, degrading effects may tend to be obscured and ignored.

Qualitative inferences about degradation can be problematic. For example, although compaction is often considered detrimental, some compaction of an extremely porous soil may be beneficial for seed germination, and tree planters know that unless soil is somewhat compacted – pressed against the roots in the planting hole – seedling survival and growth may be threatened. One cannot definitely infer degradation from changes in bulk density or porosity or from pore size distribution data unless one knows how the initial and final values relate to the optimum values. The optimum may differ for different soils in different situations: particular soil pore size distribution may be optimum on a wet site; a greater abundance of fine pores, at the expense of the larger pore size classes, may be better on a dry site. Such considerations indicate that, particularly where changes do not result in extreme values, the interpretation of degradation from measured changes may sometimes be difficult and uncertain.

2 MECHANICAL SITE PREPARATION

Research on site preparation impacts is often confined to situations where the right equipment is used under the right soil moisture conditions. The work does not necessarily reflect the operational realities of often having to use sub-optimal equipment under sub-optimal conditions. Consequently, estimating the extent and seriousness of soil physical degradation which occurs as a consequence of mechanical site preparation can be difficult.

Moving machinery over the land and pulling implements (e.g., mounders, disk trenchers, plows) through the soil can result in some degradation, particularly when the soil is wet. Wetter soils have lower shear strength, and soil compactibility is affected by water content (Sowers and Sowers 1970). Compaction, involving at least some collapse of large pores to make smaller ones, and an increase (with slight compaction) or a decrease (with severe compaction) of the small-pore volume, results in changes in root penetration (Minore *et al.* 1969), water retention and aeration. Fine-textured soils tend to resist such damage when they are dry, because of bonding by the clays; however, they are very susceptible to serious damage when wet, because puddling results in loss of the larger, aeration pores. Smearing of clays and surface pore clogging are often observed where plows are used for site preparation on wet, fine-textured soils. The rate of recovery from such impacts is a topic which needs study.

Mechanical site preparation may be employed partly to reduce bulk density after compaction, resulting from harvesting operations. However, in a study by Gent *et al.* (1983), the soil bulk density was not reduced by site preparation consisting of a shearing, burning, chopping and bedding treatment. Saturated hydraulic conductivity and aeration porosity were either reduced or not significantly changed by site preparation. Gent and his colleagues noted that compressive and shearing forces exerted during site preparation and harvesting extend below the depth reached by the equipment. They concluded that site preparation did "not improve and may actually further deteriorate physical properties of the original, noncut surface under the bed", and that root penetration below the depth of preparation may be impeded.

In another study, on different soil, Gent *et al.* (1984) examined the effect of disking as a site preparation method. Bulk density, aeration porosity and saturated hydraulic conductivity were either unaffected or improved (reduced, increased and increased, respectively) relative to post-harvest levels on untreated plots. In all cases, insignificant change was found below 15 cm. They concluded that disking was effective in restoring soil physical properties to pre-harvest levels in the upper 7-12 cm. In contrast, a chop-and-burn treatment on skid trails seriously reduced saturated hydraulic conductivity at depths of 0-23 cm.

Ritari (1977) compared scalping, "shoulder plowing", "tilt plowing", chain rototilling and mounding in terms of their effects on soil physical properties, on a Finnish site where thick mor humus occurred over till containing abundant fines. (The "shoulder plowing" scraped surface material away with the plow. "Tilt plowing" turned a furrow on which seedlings could be planted.) Ritari found that shoulder plowing resulted in lower soil porosity, compared with porosity of undisturbed soil. Scalping also resulted in a slight, but insignificant reduction; other treatments increased porosity. Infiltration rates were low on scalped and shoulder-plowed areas, in comparison with those on undisturbed soil, but were somewhat more comparable to soil from which the humus layers had been carefully removed. In all cases, porosity was 45% or more; infiltration rates were 60 mm/h or more.

Despite some changes in magnitude, it is not clear that the new magnitudes would be growth-limiting; consequently, it might be argued that little or no degradation of the measured properties may have occurred. Soil temperature measurements indicated that the number of degree-days at the 5-cm depth were increased by all treatments.

In the southern United States, clearcut areas were compared after loblolly pine had been planted within a year after site treatment on four areas: a) untreated, b) burn slash, c) chop and burn, and d) cut with KG blade, cultivate, and burn slash (Stransky 1981). Soil bulk density was evaluated after three growing seasons; pine growth was evaluated after five growing seasons. Bulk density and tree growth were greater with treatments (c) and (d) than with (a) and (b). The better growth was tentatively attributed to greater reduction of hardwood competition, despite the increased compaction.

Erosion attributable to mechanical site preparation has seldom been quantified. A study in Mississippi compared four recently logged watersheds which had been subjected to different kinds of site preparation: a) brush chopping, b) shearing and windrowing, c) bedding on contours, and d) untreated (Beasley 1979). After treatment, all watersheds were limed and sown with subterranean clover seed. First-year erosion losses were 12.5, 12.8, 14.2 and 0.6 t/ha, respectively; second-year losses were 2.3, 2.2., 5.5, and 0.1 t/ha. Channel scouring was a major source of sediment in watercourses in the prepared watersheds. Most of the first-year erosion occurred in months when storm flow was high. Treatment caused great variation in the amount of storm flow, but much less variation in the suspended sediment concentration in storm flow. Concentrations were 2471, 2837, 2808 and 2127 mg/L, respectively, for the four watersheds. In the second year, storm flow decreased on all watersheds, and suspended sediment concentrations also decreased.

In addition to the physical effects, there may be soil biological and nutritional effects of mechanical site preparation. Because forest floor material commonly contains abundant mycorrhiza-forming fungi, and has often been used as inoculum for tree seedlings, it is interesting to consider the implications of forest floor removal for mycorrhiza development. A study by Perry *et al.* (1982) suggested that scalping the forest floor does not significantly affect the number of mycorrhizal root tips on Douglas-fir, measured 16 years after site treatment. However, a study by Alvarez *et al.* (1979) found that white fir (*Abies concolor*) seedling growth and the presence of mycorrhizae on the seedling roots were favoured by the absence of organic layers. Although such findings suggest that ample inoculum may be available in soil horizons below the forest floor, deep scalping which removes all horizons occupied by fungi might cause nutritional problems if uninfected seedlings are planted. Impaired P nutrition is often the most serious problem associated with non-mycorrhizal trees; somewhat impaired uptake of N, K, Cu and Zn might also be observed (Harley 1969; Tinker and Gildon 1983). Infection as a result of natural inoculation by spores in the scalped area or from root egress into soil occupied by fungi should make the non-mycorrhizal condition temporary, if it should develop on treated sites.

A study in East Texas compared (a) cut and leave, (b) cut, leave and burn, (c) chop and burn, and (d) shear, pile and disc, in terms of their chemical effects, evaluated 5 years after treatment (Pehl 1984). For the 0-8 cm depth, soil total N and extractable Ca were lowest in (d); otherwise there were no significant differences. This indicates that the disc treatment simply redistributed nutrients somewhat deeper in the soil. Stands of loblolly pine on (d) tended to have more stems of larger size, in comparison with other treatments. Foliar N concentration was lower for (d); otherwise there were no significant foliar nutrient concentration differences, where N, P, K, Ca and Mg were measured. The investigator in that study tentatively attributed the lower foliar N concentration on (d) to growth dilution; however, this does not explain why the other nutrients were not similarly affected. It is conceivable that N nutrition was really impaired by the treatment and that amelioration of another, more limiting, factor may have been responsible for the increased growth.

The amounts of macronutrients removed by scalping a 1 cm thick humus layer vary. Approximate amounts, in kg/ha, are 150 (N), 20 (S), and 15 (P,Ca,Mg,K), judging from bulk density and concentration data of Gessel and Balci (1965) and Carter (1983). Although such removals may represent only a small fraction of the total soil capital, they sometimes represent a much larger fraction of the available nutrients, particularly in the case of N (Dyck 1976), P (Bockheim *et al.* 1973; Curran 1984) and S (Will and Youngberg 1978). With narrow treated areas, tree roots may soon extend into adjacent soil, and nutrient redistribution gradually occurs as the stand develops, due to litterfall and other nutrient cycling processes. Thus, the detrimental nutritional impact of small scalps is likely to be temporary. With extensively scalped areas, the impact may be more serious and more permanent; tree nutrition and growth may be significantly impaired (Nyland *et al.* 1979).

A study in the Cariboo and Prince George Forest Regions used foliar analysis to evaluate white spruce nutrition on untreated clearcut areas and on areas where surface horizons had been scalped during harvesting or mechanical site preparation. The frequency of serious N and Cu deficiencies was much higher and the average severity of N and Cu deficiencies was worse on scalped areas than where no treatment had been done (Ballard 1984). (Table 1).

TABLE 1. Frequency and severity of nutrient deficiencies in relation to site preparation, for sampled plantations in the Prince George and Cariboo Forest Regions (from Ballard 1984)

Nutrient	**Percent of Plantations with Class 4 & 5 Deficiency**[a]			**Nutrient Status Class Averaged for Plantations**[a]		
	NSP[b]	**MECH**	**BURN**	**NSP**[b]	**MECH**	**BURN**
N	0	30	64	2.73	2.96	3.65
Fe	8	20	59	2.16	2.80	3.44
Cu	0	50	45	2.12	2.90	3.24
Mg	20	10	31	3.12	2.90	3.24
B	0	0	9	1.96	2.06	2.09

[a] Nutrient status classes range from 1 (ample) to 5 (extremely deficient). (Where different deficiency levels occurred in different sampling strata within a plantation, data for that plantation were calculated proportionately.)

[b] NSP - No site preparation (n=5); MECH - scalping of surface soil horizons, but no burning (n=5); BURN - slashburning (n=11).

Windrowing of logging residues can cause major redistribution of nutrients on a site. A study in Florida found that 6% of the area was occupied by windrows, which represented more than 10% of the site's total N and between 15 and 40% of the site's organic and extractable P, K, Ca and Mg (Morris *et al.* 1983).

Near Carp Lake, in the Prince George Forest Region, a windrowing and burning treatment was evaluated in terms of effects on nutrients and spruce seedling growth (Ballard 1985). Essentially all the forest floor between windrows was removed by the windrowing operation, leaving exposed mineral soil. Estimated N losses by this forest floor removal amounted to about 475 kg/ha. Except where alder invaded, spruce growth between windrows was significantly slower (average leader length 30% less and average total height 25% less, 8 years after planting) and foliar N was significantly lower (average 0.94% vs 1.01% N) than for spruce planted within the windrows.

3 SLASHBURNING

Slashburning has some physical effects on soils. In some cases it induces or aggravates serious hydrophobicity, resulting in reduced infiltration and reduced retention of water (Debano and Letey 1969). The consequent increases in runoff sometimes result in serious erosion. Loss of the forest floor's protection against raindrop impact and destruction of root mats may also contribute to increased erosion after burning.

Light burns, which remove slash cover and blacken the surface, may lead to increased soil surface temperature maxima which, if too extreme, could be lethal for young seedlings. However, the effect is transitory, because of shading by pioneer vegetation. More severe burning can result in a smaller increase (or even a decrease) of surface temperature maxima, because reduction of surface organic layer thickness can allow more heat to be conducted down into the mineral soil. For the same reasons, subsurface temperatures during the growing season may be increased as a result of burning, leading to increased growth in areas of cold soils.

Some nutrients are lost by volatilization during combustion. As much as 60-80% of the N and S in fuels may be lost by this pathway (Allen 1964; DeBell and Ralston 1970). However, the effect of such loss may be more or less compensated (at least for a while) by greater availability of the N and S fractions that remain. Ash nutrients tend to be highly soluble and highly available. However, anion adsorption by charcoal and ash (Beaton *et al.* 1960) may have some detrimental consequences, e.g., in terms of phosphate availability. Post-fire pH may be excessive for seedlings of some species until some leaching of bases and reacidification of surface soils has occurred. The high pH resulting from burning also may limit availability of several trace metals (Mn, Fe, Zn, and Cu), although one study (Czapowskyj 1979) found higher foliar Fe levels on a slashburned site than where slash had been either physically removed or left on the site.

After a fire, Fe availability to plants may be limited not only because of the effect of higher pH, but also because siderophore production by soil microbes may be dramatically reduced (Perry *et al.* 1984). The siderophores, mobile organic complexes of Fe, are essential to prevent or limit Fe deficiencies in plants growing on some soils where soluble, ferrous iron is not very abundant.

A study by Bråathe (1973), of slashburning effects in Norway, offers an instructive example of the need to examine long-term as well as short-term effect of site preparation. He found that although short-term tree growth was enhanced as a result of burning, long-term growth was impaired in some (but not all) ecosystems studied. After about 8 years, trees on some burned areas were shorter than trees that had been planted at the same time on similar, but untreated areas. A hypothesis to account for this is that burning may enhance early growth for a number of reasons, e.g., highly available nutrients from ash, reduced competition, and more favourable microclimate. Although the site N capital may be reduced by volatilization, it is possible that a larger fraction of the residual N becomes available as a result of burning. After a few years, however, as a result of increased competition from other plants and concomitant microclimate change, together with some redistribution of nutrients into less available forms, growth rates on burned sites may be reduced.

Effects of slashburning on tree growth and nutrition have been dissimilar in various studies in British Columbia. A current study at Mission Tree Farm has found, in one burned area, some indication of decelerating tree growth after several years, analogous to Braathe's observation (M.P. Curran, personal communication). Other burned areas studied, however, did not indicate such "growth crossover" trends. Knight (1964) found poor growth and poor N status of Douglas-fir on burned sites. In salal-dominated ecosystems on Vancouver Island, Vihnanek (1985) found that Douglas-fir growth and nutrition were often superior and never significantly worse on burned than on unburned areas, even several years after treatment. At least in part, his observations appear to reflect relatively long-term reduction of salal competition (e.g., for nutrients) as a result of burning. In the British Columbia Central Interior, Ballard (1984, 1985) found that despite poorer nutrient status of spruce on burned compared to unburned sites (Table 1), growth was better. The superior growth on burned sites is probably a consequence of higher growing-season soil temperatures in the root zone, because of forest floor and slash removal by burning. On undisturbed sites, soil temperatures in the region are commonly far below optimum for spruce growth. Root zone soil temperature can be increased by removing shading vegetation and scalping the surface organic layer, benefiting spruce seedlings in these cold areas (Dobbs and McMinn 1977).

In the studies by Ballard (1984, 1985), burning was detrimental to the N, Cu and Fe status of spruce. Based on other studies cited above, it seems likely that volatilization loss of N, pH effects on solubility of Cu and Fe, and effects on siderophores are responsible. With better growth on burned sites, it is possible that growth dilution of these nutrients is also implicated. However, because other nutrients do not appear to be significantly affected, as indicated by the example in Table 2, it seems unlikely that growth dilution is the major reason for the effects on N, Cu and Fe. Although slashburning in this case resulted in better growth, the concomitant development of nutrient deficiencies indicates that growth remains below potential.

TABLE 2. Foliar nutrients in a white spruce plantation, Willow-Bowron area. The site was planted in 1979, sampled in 1983 (Ballard 1985)

Foliar Nutrients	Slashburned Area	Unburned Area
N, %	1.07[a]	1.37
P, %	0.194	0.221
K, %	0.63	0.57
Ca, %	0.54	0.47
Mg, %	0.09	0.11
Mn, ppm	579	776
active Fe, ppm	23[a]	38
Zn, ppm	67	76
Cu, ppm	1.7[a]	2.4
B, ppm	15	14

[a] Differences between burned and unburned are significant at $P = 0.01$.

4 CONCLUSIONS

In conclusion, site preparation can affect physical, chemical and biological properties of the soil. Where erosion is increased, or where extreme values of soil properties are found, the inference of soil degradation can be straightforward. Where effects on productivity are invoked as evidence of degradation, the net beneficial and detrimental effects may obscure the seriousness of degradation. Even where site preparation yields positive results, there may be some soil degradation, which is keeping productivity below potential. This may be a price we are willing to pay because of the net benefits. However, the prospect of doing better stimulates a continuing search for alternative, cost-effective site preparation methods, which can attain site preparation objectives and improve critical soil properties, while avoiding soil degradation.

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SESSION 2

Forest Soil Degradation/Productivity Relationships

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T. Lewis
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SESSION 2 DEGRADATION/PRODUCTIVITY

SOIL DISTURBANCE, DEGRADATION AND PRODUCTIVITY

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ABSTRACT

Soil disturbance often has no significant negative impact and may have a beneficial effect on tree establishment and growth. Therefore, soil degradation, not disturbance, should be the term used to describe soil impacts resulting in a demonstrated loss of site productivity. The level of soil degradation depends on the type, degree and extent of soil disturbance and on the sensitivity of the impacted soil and tree species. Surveys utilizing ground-based sampling are essential to determine the areal extent of particular types of disturbance. Characteristics of these types need to be known to explain impacts and guide preventative and rehabilitative actions. Observations and measurements of "soil disturbance" plantations are becoming a prime source of soil degradation information. Results of forest soil degradation research, particularly aspects of soil displacement, are used to illustrate the magnitude of impacts and some of the processes involved.

1 INTRODUCTION

Since this workshop closely follows one held in February 1983 dealing mainly with degradation of agricultural soils (van Vliet 1983), it seems appropriate to make some comparisons between agricultural and forest production. Agriculture in most instances requires entry onto the land several times a year, resulting in a high potential for accumulated damage to soil. In forestry, entries are more likely to be in the order of two to three times per rotation, i.e., over a 60- to 100-year period. These relatively infrequent entries reduce the chances of forest soil degradation, but mean there are fewer opportunities to monitor crop performance or routinely apply amendments compared with those associated with agricultural production. Also, since it takes so long for a forest crop to mature, there is a tendency to believe that nature and time will correct any early soil damage. This is often true, but productivity losses occurring even in the early part of a rotation will eventually mean reduced yield. Severe soil disruption caused by mass wasting, for instance, may even result in essentially permanent reduction in productivity (Trustrum *et al.* 1984). Regardless of how long productivity is affected, the fact remains that if the magnitude of losses can be predicted, costly ameliorative action must be taken or estimates of annual growth rates reduced, and reductions in annual allowable cuts considered.

2 SOIL DISTURBANCE

Soil disturbance is defined here as any abrupt change in the physical, chemical or biological properties of a soil. It is caused either naturally (windthrow, landslides, flooding, wildfire), by human activity (road construction, yarding, site preparation) or as the result of a combination of the two. Soil disturbance associated with site preparation is designed to be beneficial for the establishment and early growth of trees. Even here, adverse side effects may occur when objectives of the operation are not well defined or the work is poorly executed. For many other forestry operations, soil disturbance is a by-product that only by chance may be beneficial to tree growth.

3 SOIL DISTURBANCE AND SOIL DEGRADATION RELATIONSHIPS

Generally, our impression of whether soil disturbance is causing forest soil degradation is based on the response of trees growing on disturbed soil. When these trees are growing poorly or appear unhealthy relative to those on undisturbed soil, we conclude that the disturbed soil has been degraded. The historical types of research conducted on skidroads, landings, mechanically prepared sites and landslides are based on this premise (Smith and Wass 1979, 1980; Herring and McMinn 1980; Wert and Thomas 1981; Smith *et al.* 1984). In this type of research we have tended to investigate the most obvious categories of soil disturbance, such as skidroads and landings. Whether this type of disturbance degrades the soil depends on the degree of the disturbance and on the characteristics of the impacted soil. With regard to the latter, most forest soils increase in bulk density with increasing soil depth and have their organic matter and nitrogen concentrated in upper horizons (see Dyrness (1965) and examples in Smith and Wass (1985)). A common pattern revealed by soil disturbance and tree growth studies is one of least tree growth on the inside, gouged portion of the skidroad, and better growth toward the outside, deposit portion (Fig. 1A). This pattern has been related, circumstantially at least, to high bulk density (Fig. 1B), low penetrability (Fig. 1C), and low organic matter (Fig. 1D) and nitrogen concentrations relative to the outer portions of skidroads or to adjacent undisturbed soil. The result can be a reduction of from 20 to 50% in height growth of trees growing on the skidroad surface (Fig. 1A). On the positive side, there may be increased summer soil temperatures, reduced vegetative competition and increased available nitrogen. These sorts of factors are likely involved in the occasional cases of enhanced tree growth on skidroads (Smith and Wass 1979).

The problem of acute iron deficiency for some plant species growing on soils with free carbonates is well known (Thorne and Seatz 1955). Marked adverse impacts can result from the displacement of upper, near-neutral horizons and exposure of lower calcareous horizons. Such soils are common in and east of the Rocky Mountain Trench. In 1950, the East Kootenay tree nursery[1] was established near Cranbrook. Among other problems with the site, including wind, rodents, frost injury and soil cracking, there was a nutrient availability problem brought on by pH values greater than 8.0. The problem spawned a series of research trials involving additions of an assortment of amendments to reduce soil pH and obtain better seedlings. Materials tested included sulphur, sulphuric acid, iron sulphate, aluminum sulphate, alfalfa compost, sawdust, stable manure and brewery waste. Cover crops were also planted. Many amendments did reduce pH and improved seedling color and vigor. However, nursery production had to be discontinued in 1967 as economically impractical. The depth of carbonate-free soil in the original profile probably did not exceed 20-30 cm, so the practice of levelling knolls and filling in depressions to allow preparation of seedbeds would have worsened an already difficult situation.

Harvesting and site preparation continue on calcareous soils and, unless very carefully conducted, soil degradation from soil displacement can be expected. Stumping operations to control root disease are particularly disrupting and result in exposure of alkaline subsoil or mixtures of subsoil with surface, non-alkaline layers. Using dilute HCl to test mineral soil at planting spots in a soil disturbance plantation, we found that 7% of the undisturbed spots had mineral soil containing free carbonates, compared with 70% of the planting spots located on tracks and deposits made by the stumping machinery. This 10-fold increase is significant when one considers that 85% of the stumped area was considered disturbed. Trees planted on this site are being monitored for survival and growth.

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[1] Information obtained from D. Wallinger, B.C. Ministry of Forests, and various issues of the B.C. Ministry of Forests Review and Annual Report.

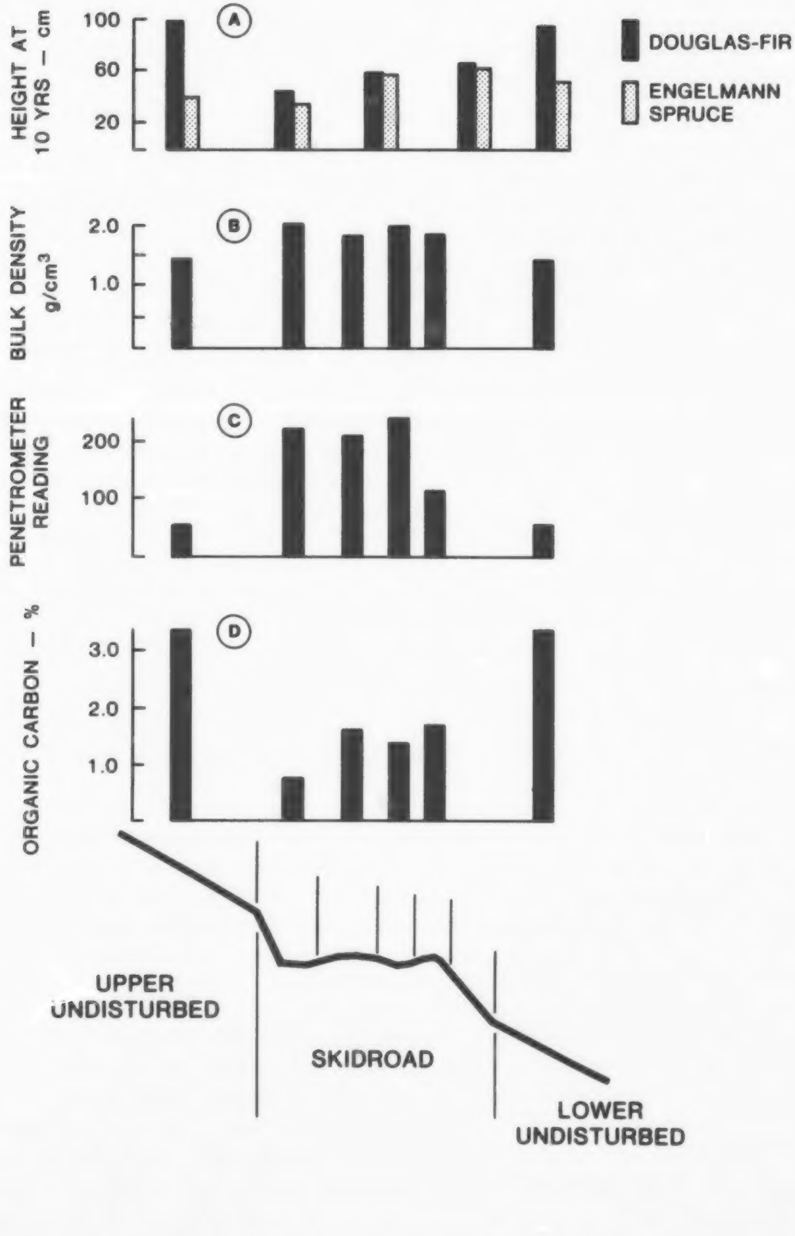

FIGURE 1. Average height growth of trees (Smith and Wass 1980) and soil properties (Smith and Wass 1985) on and adjacent to skidroads near Horsefly Lake, B.C. Values for soil properties of the lower undisturbed area are inferred from measurements made in the upper undisturbed area. (A) Height. (B) Bulk density of mineral soil (10- to 20-cm depth). (C) Cone penetrometer readings at 12.5-cm depth in mineral soil. (D) Percentage organic carbon of mineral soil (10- to 20-cm depth).

4 DETERMINING OVERALL PRODUCTIVITY EFFECTS

Even knowing the specific growth impacts caused by certain types and degrees of disturbance in particular types of soil, the problem of estimating overall reductions in productivity remains. These estimates are necessary to justify adjustments to annual allowable cuts and expenditures for rehabilitation, and are needed to judge net benefits of harvesting and silvicultural treatments.

Surveys must be conducted to determine the type, degree and extent of disturbance. An intersection length procedure modified from one developed for determining the area affected by root disease (Bloomberg *et al.* 1980) has proved efficient for distinct, regular disturbances such as those caused by haul roads and constructed skidroads. Point-interval surveys (Bockheim *et al.* 1975), using, for instance, 3 m intervals along transects, are appropriate for the more complex mosaic of disturbance caused by site preparation and random-pattern log skidding. The point-interval system also allows other details to be collected at each point. A method using random starting points and random orientation of transect lines has been developed by Howes *et al.* (1983). Computerized digital imaging of large-scale (1:500 to 1:1000) aerial photographs is a promising technique, but studies of its application to forest soil disturbance are required.

Surveys serve to determine the prevalence of disturbance types. The expected response of trees growing on each of these types can be based on the growth impact studies discussed earlier, or eventually on results from soil disturbance research plantations. Overall productivity losses can be estimated on a simple prorating basis. For a disturbance type occupying 30% of the ground surface and causing a 50% reduction in height growth, the prorated loss would be (50 x 30) ÷ 100, or 15%. This magnitude of loss has been estimated to result from ground skidding operations on some sensitive interior British Columbia sites (Smith and Wass 1980) and in Oregon (Wert and Thomas 1981). If tree growth is severely reduced over a large part of the rotation, then the resulting trees will not be economically harvestable. The loss for trees affected would then be 100% and, in the foregoing example, 30% overall. Whether trees growing in undisturbed spots benefit from being adjacent to slower growing trees in disturbed areas is a question for further research.

5 IMPROVING OUR INFORMATION BASE

In addition to continuing historically based studies on a wider variety of sites, we need to utilize results from soil disturbance plantations. In these, the growth of planted trees is monitored on specific disturbed spots and on nearby undisturbed spots. Although it takes longer to obtain results from plantations, variables can be better controlled than with historical studies, e.g., spacing, vegetative competition and date of establishment. Additionally, important soil, ecoclimatic and physiological characteristics can be monitored to help explain growth responses. Early results from these types of studies in British Columbia have underlined how responses to disturbance can differ with relatively minor differences in soil characteristics (Smith and Wass 1984). Cutovers with soils of low (<4%) clay contents were stumped for root-disease control without nearly the same adverse impacts that result from similar operations on soil with a higher (9-13%) clay content. This occurred despite the fact that both soils were classed as gravelly sandy loams. Disturbance on the former may, in fact, have been beneficial to early tree growth through reduction of vegetative competition. In contrast, as indicated by reduced tree growth, the benefits of this reduction on the finer soil were likely countered by an increase in surface soil density and resistance to penetration (Smith and Wass 1984).

Plantation studies can also elucidate tree survival problems. During the dry summer of 1985, planted trees were subjected to heat and drought stresses on many sites. In one of our plantations in which average first-year survival was 25%, trees survived best (35%) on the high-density skidroad surface and least (17%) on loose berm and sidecast material. In another 1985 plantation, survival was 85-90%. Mortality was again higher in loose deposits (30% for Douglas-fir and 14% for lodgepole pine) than in the undisturbed areas (14 and 6%, respectively) or on tracks (8 and 2%, respectively). The bare, compact soils may have retained the highest proportion of moisture from the few showers that did occur through an absence of intercepting foliage and an increase in soil micro-porosity.

6 SUMMARY AND CONCLUSIONS

Research on soil degradation has tended to move from general studies with little direct control of variables to studies aimed more specifically at processes. One might argue with this order, but documentation on productivity impacts in British Columbia was needed quickly to get attention. This documentation came most logically from the well-defined and widespread disturbance involving soil displacement with its high potential for soil degradation, i.e., skidroads, landings and landslides. Other types of disturbance with less obvious potential for degradation such as caused by burning, groundwater interception and mechanical compaction need similar attention. Agencies are now formulating guidelines designed to limit soil degradation. To be fair, complete and effective, they will require a greater ability to understand and predict specific tree growth responses to specific types of soil disturbance on specific types of soil. Such explicit information will be gained most reliably from plantation studies with detailed tree performance and environmental monitoring.

To guide monitoring and regulation, soil disturbance and soil degradation relationships will need to be extrapolated utilizing soil disturbance surveys. For this work, the same disturbance types defined in terms of growth impacts must be part of the survey classification system.

The final task of estimating productivity effects for whole clearcuts requires knowledge of compensatory effects of disturbance, such as reduced vegetative competition and increased biological activity. Consideration must also be given to any positive growth response of trees situated in undisturbed (humus intact) portions of clearcuts resulting from the proximity of these trees to relatively slow-growing ones established on degraded soils.

An ability to predict impacts on the basis of soil conditions and of the nature of proposed forestry operations will allow decisions to be made for alternative plans or practices.

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SESSION 2 DEGRADATION/PRODUCTIVITY

INTERPRETING THE EFFECTS OF BROADCAST BURNING ON FOREST PRODUCTIVITY

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ABSTRACT

Broadcast burning is an important forestry practice that can often achieve several silvicultural objectives. As a result, the practice can affect forest productivity in a multitude of ways. Broadcast burning that improves reforestation and controls competing vegetation may enhance the performance of managed forests, increasing the apparent site productivity. Site nitrogen is generally reduced by broadcast burning, which may eventually reduce soil nitrogen and long-term soil productivity. A thorough analysis of how these various effects of broadcast burning affect the operational environment of commercial species and their subsequent growth is necessary for quantifying any changes in forest productivity. Simply measuring a loss of site nitrogen is not sufficient to quantify this impact. Several scenarios of how changes in the operational environment can affect forest productivity are discussed.

1 INTRODUCTION

Broadcast burning is an important silvicultural operation in many parts of the Pacific Northwest. Justification for its use ranges from the preparation of a mineral soil seedbed for natural or direct seeding, to the control of competing vegetation around newly planted seedlings. These benefits, however, are not achieved without some potential adverse effects. A major issue affecting its use in western Oregon is the effect that smoke from broadcast burning has on air quality (Fahnestock and Agee 1983). Broadcast burning can also expose mineral soil, increasing the potential for erosion of the surface soil (Amaranthus and McNabb 1984). The loss of nutrients, particularly nitrogen, during broadcast burning has been a major issue surrounding its use for decades (Isaac and Hopkins 1937; Youngberg 1953; Little and Klock 1985). These losses are becoming more of an issue as the intensity of forest management increases.

The potential for nitrogen lost during broadcast burning to affect soil productivity is, indirectly, quite substantial. Historically, large amounts of nitrogen have been lost during wildfire or slashburning (Zavitkovski and Newton 1968; Grier 1975). Modern broadcast burns of low intensity reduce the amount of nitrogen lost, but it is still not unusual for about 10% of the total site nitrogen to be lost in a single broadcast burn (Little and Klock 1985). The proportion of site nitrogen loss can be much higher when most of the nitrogen is stored in the forest floor where it is more easily volatilized by burning (Boyer and Dell 1980). The potential for losses of site nitrogen to affect site productivity is supported by the fact that most Douglas-fir forest sites respond to nitrogen fertilizer (Miller *et al.* 1986). Furthermore, the percent response and duration of the response to nitrogen fertilization increase on poorer sites that generally have lower site nitrogen. Kraemer and Hermann (1979) were unable to substantiate, however, that losses of site nitrogen reduce soil nitrogen after 25 years, although some trends were apparent.

Predicting the effects that broadcast burning has on forest productivity is a difficult task. Such an effort must rely heavily on professional judgment about how changes in the forest ecosystem, as a result of management activities, are affecting the survival and growth of seedlings, trees, and ultimately the forest stand. Computer models, such as FORCYTE, are designed to aid this analysis with a numerical solution to the problem (Kimmins 1985). Regardless of how broadcast burning affects forest productivity, predicting its effect must be validated with quantitative data. Unfortunately, these data are difficult to obtain and few intensive investigations are underway to obtain the information.

A crucial element to interpreting the effect that broadcast burning has on forest productivity is understanding how it affects the biological processes important to tree growth. This understanding is a necessary prerequisite for interpreting how forests respond to change. It applies whether one is evaluating the effects of broadcast burning on the growth predicted by models such as FORCYTE, determining the applicability of results in the scientific literature to local areas, or designing new research.

Numerous variables may be affecting the biological processes of the forest simultaneously; however, interpreting these effects in the broader context of the forest ecosystem has been a major limitation of most research on broadcast burning. This limitation can be overcome by emphasizing and understanding how the operational environment and a change in that environment affects the growth of seedlings, trees, and stands (McNabb and Campbell 1985). A discussion of how some soil, site, and stand variables may affect the operational environment following broadcast burning, and how changes in this environment may affect forest productivity, are the objectives.

2 BROADCAST BURNING AND THE OPERATIONAL ENVIRONMENT

Because of the potential for broadcast burning to affect a large number of soil and site variables, the stand response to burning depends on site-specific conditions. Identifying and quantifying changes in the most important site variables that affect growth is a necessary prerequisite for determining what the long-term effects of broadcast burning are likely to be on stand yield. As a first step in this process, a decision must be made as to what to measure. Although many variables may be considered, most do not directly affect growth. Thus, the selection of variables must emphasize those that alter the operational environment of the seedling, tree, and stand (McNabb and Campbell 1985).

The concept of an operational environment is not new. It was defined by Mason and Langenheim (1957) and Spomer (1973), and used by Hobbs (1984) to identify factors critical to the reforestation process. Briefly, the concept of an operational environment includes only those operational factors within the total environment which are capable of directly affecting the physiology of a species. Operational factors include water, light, gases, heat, and nutrients, i.e., those factors which have mass or possess energy and can interact with the plant. An interaction means there is a mutual reaction, that some physiological change is effected in the species as a result of a change in the operational environment, and vice versa. Thus, these measurements must emphasize variables such as the flux of heat energy between the atmosphere and a burned soil surface, rather than temperature which is a unit of measurement.

Broadcast burning, as do many other forestry practices, alters a large number of soil, site, and stand variables that influence operational factors. Changes in operational factors (i.e., through forestry activities) alter the operational environment and, hence, the measure of forest productivity (Figure 1). This relationship allows for site-specific differences or changes in the operational environment. Furthermore, the effect that changes in the operational environment may have on productivity may be temporary, seasonal, or occur as an infrequent event. Depending on the season or period of the rotation, one operational factor may be more important than the others. Adopting this relationship to interpreting the effect of broadcast burning on long-term productivity is complex, because it focusses on the natural processes occurring in the forest ecosystem.

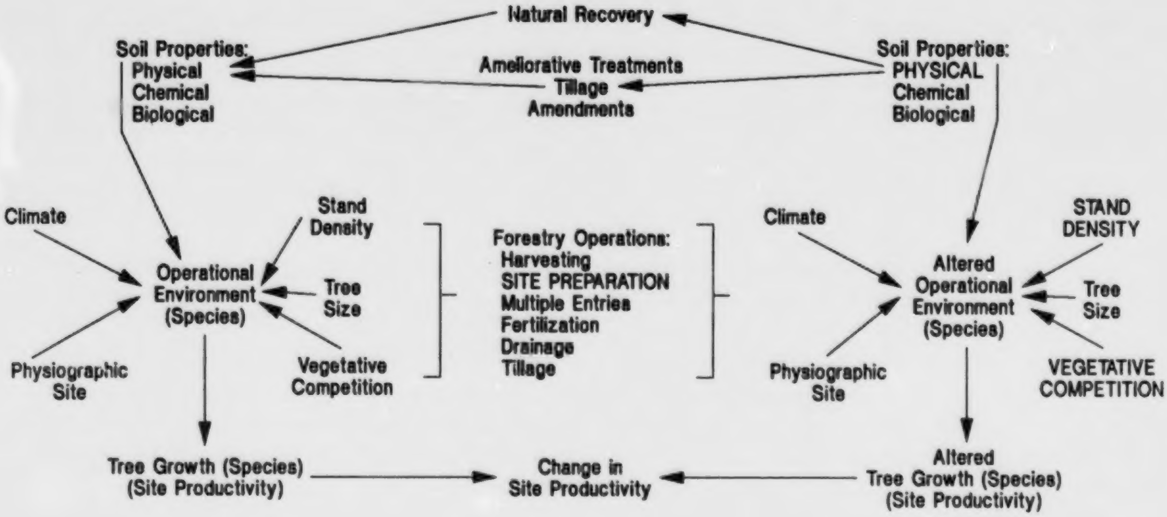
Natural Recovery
Soil Properties:
Physical
Chemical
Biological
Ameliorative Treatments
Tillage
Amendments
Soil Properties:
PHYSICAL
Chemical
Biological
Climate
Stand Density
Operational Environment (Species)
Tree Size
Physiographic Site
Vegetative Competition
Forestry Operations:
Harvesting
SITE PREPARATION
Multiple Entries
Fertilization
Drainage
Tillage
Climate
STAND DENSITY
Altered Operational Environment (Species)
Tree Size
Physiographic Site
VEGETATIVE COMPETITION
Tree Growth (Species) (Site Productivity)
Change in Site Productivity
Altered Tree Growth (Species) (Site Productivity)

FIGURE 1. If broadcast burning is to affect site productivity, it must change the operational environment of the species that is used to indicate productivity. The operational environment is changed by altering basic operational factors, such as water, nutrients, and light. Many soil, site, and stand variables can affect the operational factors important to the operational environment (McNabb and Campbell 1985).

3 IMPORTANT VARIABLES AFFECTING THE OPERATIONAL ENVIRONMENT OF BROADCAST-BURNED SITES

3.1 Soil Properties

A review of the literature readily demonstrates that broadcast burning can affect a large number of soil properties (Wells *et al.* 1979; Feller 1982). Unfortunately, the changes in soil following broadcast burning are highly variable. For a specific soil property, the property may not change or it may increase or decrease, depending on the study. This inconsistency greatly complicates the interpretation of how specific changes in a soil property affect forest productivity. It does reinforce the need to measure changes in the soil environment in terms of change in the operational factors and the operational environment of the site, rather than simply to list changes in soil properties.

As a result of changing the thickness, type, or color of the litter or other soil cover, broadcast burning induces changes in the soil physical environment, such as the flux of heat or moisture at the soil surface. These are relatively short-term changes in the operational environment, but they can have a major effect on future stand yield by influencing reforestation of a site.

A change in soil nutrition as a result of broadcast burning is generally the most important soil-related issue affecting the use of such burning practices in the Pacific Northwest. Although the concentration and availability of several nutrients may be altered by broadcast burning (Feller 1982; Little and Klock 1985), the loss of site nitrogen is generally considered the most important. The two principal observations supporting this concern are: 1) the generally good response of Douglas-fir stands to nitrogen fertilizers; and 2) the good relationship between the mass of soil or site nitrogen and site productivity (Figure 2). Based on the latter observation, a reduction in site nitrogen following broadcast burning will result in a proportional decrease in site productivity. Although the general relationship suggests that this may be a reasonable

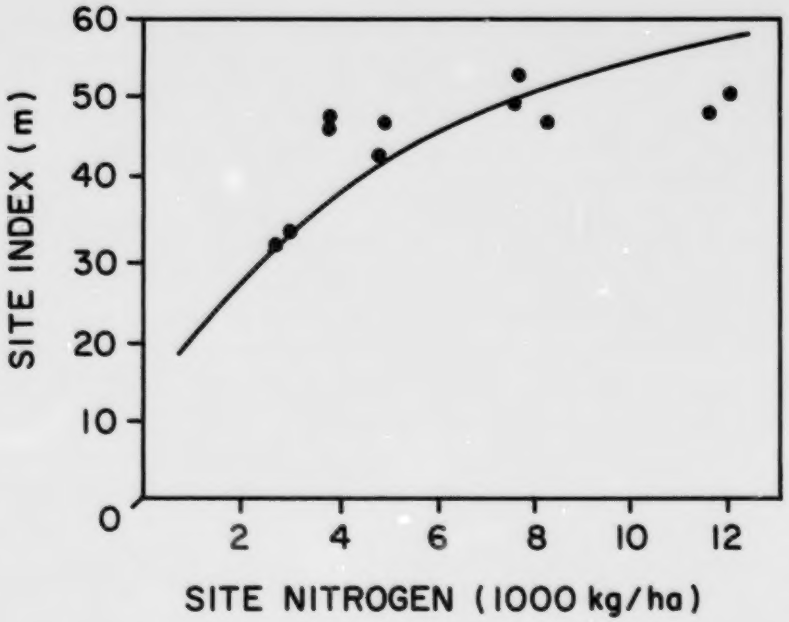

FIGURE 2. General relationship between total site nitrogen and site index at 100 years for 11 soil series in the central Coast Range of Oregon (Jerry Richeson, Eugene District, Bureau of Land Management, unpublished data).

assumption, the relationship may change during the life of a forest at a specific site. This is particularly true for forest types where major wildfires have reduced site nitrogen, and site nitrogen is subsequently increased through large additions of nitrogen by dinitrogen fixing organisms (Cromack *et al.* 1979).

Dinitrogen fixation by *Ceanothus* or *Alnus* species can add several thousand kilograms per hectare of nitrogen to some forest sites in the first few decades following wildfire or harvesting and broadcast burning. In old-growth forests that are several hundred years old, similar amounts of nitrogen can be added through dinitrogen fixation by lichens and in downed logs. Additions by lichens are greatest after a stand matures and additions by downed logs depend on their numbers and state of decomposition (Sollins *et al.* 1980). As a result of these many and varied additions during the life of a native forest, old-growth forests often contain much more nitrogen than is present immediately following the disturbance responsible for its establishment.

The amount of nitrogen lost from a site during broadcast burning can differ by a factor of about 10. This loss depends on the amount of fuel, the amount of fuel and forest floor actually consumed by burning, and the distribution of site nitrogen between the fuel, forest floor, and soil components. The greatest loss of nitrogen normally occurs during major wildfires and fall slashburning of poorly utilized materials. Grier (1975) estimated that a wildfire on the east slope of the Cascade Mountains of Washington reduced site nitrogen by 907 kg/ha. This estimate excluded the nitrogen lost in burning the foliage, limbs, and bark from the standing trees and other vegetation. Based on several studies of slashburning prior to about 1960, Zavitkovski and Newton (1968) estimated nitrogen losses of 750 kg/ha from forests west of the Cascade Mountains. Nitrogen losses from slashburning in coastal British Columbia are estimated to range between 600 and 1000 kg/ha (Feller *et al.* 1983). These values probably represent the upper limit of nitrogen loss from these forests (Klock and Grier 1979).

Current efforts to improve air quality by reducing fuel consumption are also reducing nitrogen losses from prescribed burning to half or less of the wildfire and intense slashburn estimates. In the western Cascades of Oregon, Little and Klock (1985) estimated that the nitrogen loss from broadcast burning ranges between 220 and 570 kg/ha; these estimates include the nitrogen lost from the foliage and branches of harvested timber. Yarding unmerchantable material, or burning under more moist conditions reduced the net amount of nitrogen lost or removed from the site. A broadcast burn during relatively moist conditions in Montana resulted in a loss of only 100 kg/ha of nitrogen from the forest floor; this was only 11% of the initial mass of nitrogen in the forest floor (Jurgensen *et al.* 1981). On a poor site in southwest Oregon, with an unusually thick forest floor because of an accumulation of logging debris from two previous harvest entries, a broadcast burn consumed 75% of the above-ground material, but volatilized only 170 kg/ha of the total site nitrogen (unpublished data).

These estimates of nitrogen loss are from several different forest types and include differences in site index and climate. Contrasting differences among these site conditions and effects of burning on nitrogen loss is one method of providing insight into the potential for broadcast burning to influence productivity. It also illustrates the importance of site-specific interpretation of broadcast burning.

For example, a common concern regarding the broadcast burning of the less productive forests in southwest Oregon is that the nitrogen loss will reduce productivity more than will a similar loss of nitrogen from the more productive forest elsewhere in western Oregon. This concern is based on a general relationship between increasing site nitrogen and site index (Figure 2); the southwest Oregon site can be included with these data from western Oregon. According to this relationship, similar losses of nitrogen from poor and good sites will result in a greater loss of productivity from the poor site.

Nitrogen loss from a southwest Oregon site, however, was lower than that from other western Oregon sites despite the high consumption of fuel and forest floor. This occurs because the biomass in the fuel and particularly the forest floor contain a relatively small mass of site nitrogen. The forest floor of these sites is typically very thin (Amaranthus and McNabb 1984); in fact, it often contains proportionally less nitrogen than other forest types in western Oregon. Furthermore, the lower consumption of biomass on these less productive sites generally cannot produce the fire intensity or duration necessary to consume all the forest floor and some of the nitrogen in the surface soil, as do wildfires or hot slashburns on more productive sites (Grier 1975; Kraemer and Hermann 1979).

Therefore, the effect of broadcast burning less productive forests in southwest Oregon may be substantially different than that in less productive forests in colder climates. The forests of southwest Oregon are in a Mediterranean-like climate of hot dry summers and cool moist winters that are conducive to high rates of decomposition (Waring and Schlesinger 1985); hence, forest floors are understandably thin. This is in contrast to forests in boreal climates where slow decomposition results in a continual increase in the thickness of the forest floor and the proportion of the site nitrogen that it contains.

The issue of whether broadcast burning is more harmful to poorer than better sites is therefore more closely related to the relative distribution of nitrogen within the site and the proportion of this amount consumed by fire, rather than to the absolute amount consumed. In general, the losses of nitrogen are usually lower on the less productive forests because longer rotations result in less frequent broadcast burns. The importance of nitrogen losses by broadcast burning, however, also depends on the ability of dinitrogen fixing organisms, both symbiotic and nonsymbiotic, to replace lost nitrogen within each forest ecosystem. The addition of nitrogen by these organisms is likewise affected by the length of rotation and other management practices which favor or exclude them. Finally, if losses of nitrogen from broadcast burning are small, it is more feasible to replace these losses with nitrogen fertilizers.

3.2 Wildfire

Wildfire is an important historical event responsible for regenerating most of the forests in the Pacific Northwest (Franklin and Dyrness 1973). These fires occurred infrequently, with rather long intervals between the catastrophic fires that killed most of the trees by crown consumption and bole heating (Lotan *et al.* 1981). Depending on the forest type, the catastrophic fires in western Washington occurred at frequencies of once every 200-1000+ years in the more moist environments (Fahnestock and Agee 1983). Low-intensity wildfires in the understory, which generally did not cause stand replacement, occurred more frequently. Although difficult to quantify, fuel consumption by wildfires is estimated to be similar to that in modern broadcast burns on an area basis (Fahnestock and Agee 1983). Fuel consumption in future broadcast burns may be less because of improved burning prescriptions designed to reduce smoke. Moreover, broadcast burns will occur more frequently than these historic wildfires if used every rotation.

In drier environments, wildfires occurred more frequently but did not necessarily destroy the forest. Near Crater Lake National Park in the high Cascade Mountains of southern Oregon, the mean frequency of wildfire ranged from 9 to 42 years depending on the sampling location (McNeil and Zobel 1980). These fires produced a relatively open forest of fire-resistant species and fire-regenerated shrubs. In the Mixed Evergreen Forest Type of southwest Oregon (Franklin and Dyrness 1973), pre-settlement wildfires occurred at an average frequency of as few as 50 years and probably were more frequent several centuries earlier when the climate was warmer and drier (Tom Atzet, Siskiyou National Forest, pers. comm.). This forest type is composed of mixed age conifers and hardwood shrubs and trees which regenerate from sprouts. Particularly in the latter forest type, the relatively thin forest floor and downed, old logs were readily consumed by wildfire. Thus, a wildfire probably did not consume large amounts of biomass on these sites, but nearly all the dead, above-ground mass present was consumed.

Wildfire may also affect the replacement of nitrogen by various types of symbiotic and nonsymbiotic dinitrogen fixation in different forest ecosystems. This may amplify any effects that wildfire has had on productivity. For example, in moist forest types with a history of infrequent wildfires, several thousand kilograms per hectare of nitrogen may be added to the site by the time a forest is 500 years old (Cromack *et al.* 1979), exceeding the highest estimated losses by wildfire or slashburning (Grier 1975; Feller *et al.* 1983).

In drier forest ecosystems where wildfires typically occurred more often, nitrogen additions by symbiotic dinitrogen fixation were most likely less than those in more moist forests because of droughty site conditions (McNabb *et al.* 1979). Additions by lichens were probably lower because of drier conditions, and both the number and longevity of mature and old-growth trees that supported lichens were less. Because of the higher frequency of wildfire, downed logs were more likely consumed in early stages of decomposition before they became major sites of dinitrogen fixation (Harvey *et al.* 1979a, 1979b).

The frequency and intensity of past wildfires have undoubtedly affected the productivity of the present forests. Although the effect of wildfire on productivity has not been quantified, in some extreme situations the effect is fairly obvious. In southwest Oregon, *Pinus attenuata* Lemm. stands are one example: these sites have a very thin forest floor, soils extremely low in organic matter, and a very low site productivity. Productivity is low despite the soils being nearly a meter deep and precipitation being higher than that in most other forests of lower productivity.

Understanding the effect that wildfire has had on existing forest productivity is a necessary prerequisite for predicting the effect that broadcast burning may have on the productivity of future forests. The basic hypothesis is that the more alike a broadcast burn is in intensity and frequency with past wildfires on a specific site, the less likely that broadcast burning will affect the future productivity of the site. In contrast, the greater the differences between broadcast burning and wildfire, the more likely that the future productivity of the forest will change. Unfortunately, data cannot be collected to test this hypothesis. The assumption supporting it, however, is that if the loss of nitrogen by broadcast burning is expected to affect forest productivity in the future, then the periodic losses of nitrogen in wildfires will have already affected the productivity of the present forests. Two hypothetical examples may help illustrate the effect that broadcast burning may have on site productivity, compared to wildfire (Figure 3).

The first example is typical of sites in the Mixed Evergreen Forest Type of southwest Oregon (Figure 3A). Wildfires were frequent (50 years) and consumed all the forest floor, most of the downed logs, and part of the crown. Dinitrogen fixation would only be a few percent of that typical of less dry forest types because of the Mediterranean climate and the absence or less effectiveness of important types of dinitrogen fixing organisms. On the other hand, broadcast burns that consume all the crown (slash) will occur less frequently (80 years) and retain part of the forest floor and woody debris. The critical question in this example is not whether broadcast burning will decrease the future productivity of these forests, but

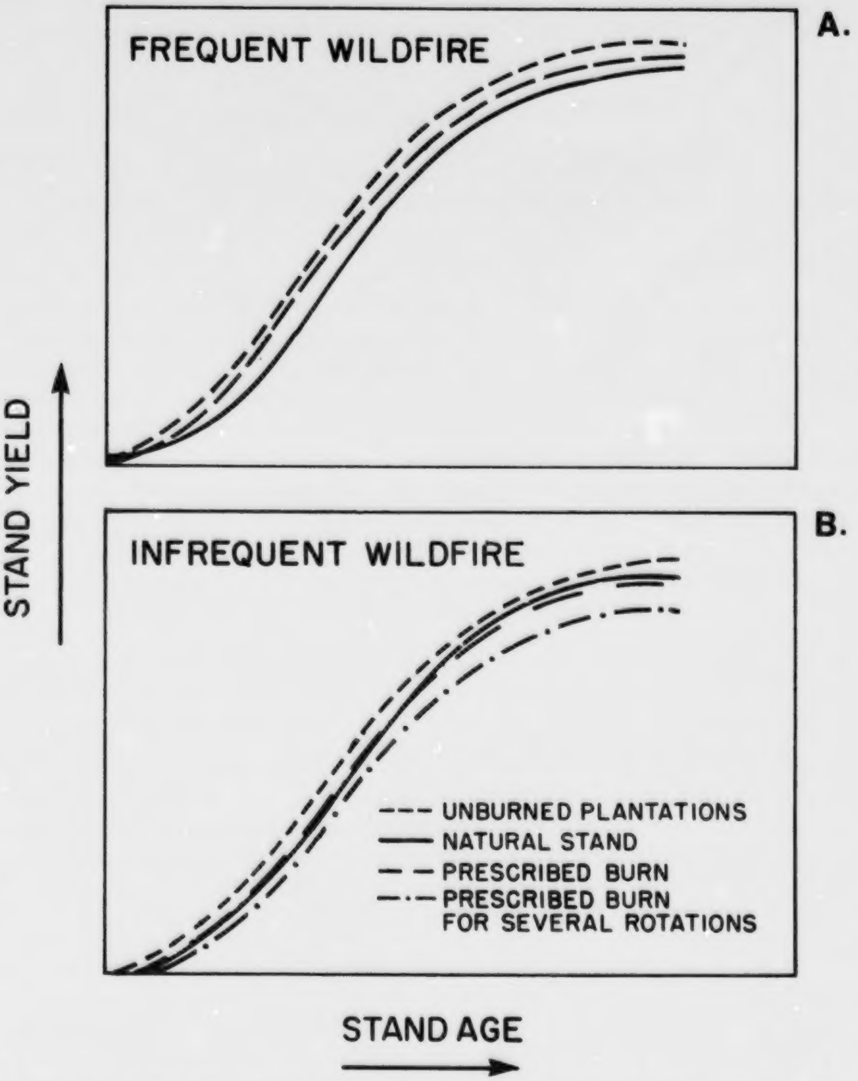

FIGURE 3. Interpretation of the effects of broadcast burning on forest productivity must consider the historical frequency and intensity of wildfires relative to the frequency and intensity of broadcast burns. The greater the difference between the effects of broadcast burning and wildfire, the more likely that soil productivity will be affected. Examples are hypothetical.

whether the productivity of future forests, compared to the present, will be increased by low intensity broadcast burns or increased even more by not burning.

The second example is typical of more mesic sites with an infrequent history of catastrophic wildfire (Figure 3B). These wildfires killed the original forest stand and consumed most of the smaller components of the tree; they also consumed most or all of the forest floor and some of the soil organic matter (Grier 1975). As the forest regenerated from the wildfire and in the centuries following, large amounts of nitrogen were generally added to the site by dinitrogen fixation. Therefore, old-growth stands of such forests currently contain more site nitrogen than was present when the forest was a young stand. The potential for the productivity of these sites to be improved by not burning is probably less than in the previous example. Furthermore, a single broadcast burn following the harvest of the old-growth forest should not decrease productivity below that of the wildfire-regenerated forest. Repeated broadcast burning of these sites on a rotation of about 50 years will greatly increase the frequency of burning over wildfires. Even with reduced intensities to meet smoke management and other soil resource protection objectives, this increase in frequency will probably lower site nitrogen more than the infrequent wildfires. This can potentially decrease site productivity. Of probably greater significance than the loss of nitrogen from broadcast burning is the effect that relatively short rotations or control of symbiotic dinitrogen mixing species may have on the ability of these sites to replace or increase site nitrogen lost during broadcast burning.

3.3 Reforestation Practices

Broadcast burning for preparing harvested sites for either natural or direct seeding, or planting, may affect the initial establishment of a managed forest differently than forests established following wildfire. This may result in apparent changes in site productivity when growth of native stands is used as the standard for estimating the future productivity of forests. The important issue in this aspect of interpreting the effect of broadcast burning on forest productivity is the speed and thoroughness that harvested sites are reforested compared to the native stand.

The successful reforestation of harvested sites ultimately depends on how reforestation practices overcome problems in the operational environment that limit reforestation. The narrow range of operational factors in which germinants are able to survive accounts for much of the site specificity of forest regeneration following slashburning (Feller 1982), and contributes to the imprecision of natural and direct seeding reforestation methods. As a result, germinants are less likely to survive on harsh sites where extremes in the operational environment are most likely to occur (Helgerson *et al.* 1982). Artificial reforestation practices, including those that artificially modify the operational environment of the seedling microsite, can generally increase the range of operational factors that seedlings can withstand and, ultimately, the success of artificial reforestation efforts (Hobbs 1984). Hence, wherever broadcast burning alters the operational factors critical to germinants and planted seedlings, it becomes a silvicultural practice capable of affecting reforestation success.

Successful artificial reforestation can often increase apparent stand yield over that resulting from native stand reforestation (Figure 4). Broadcast burning can contribute to this success in a number of ways.

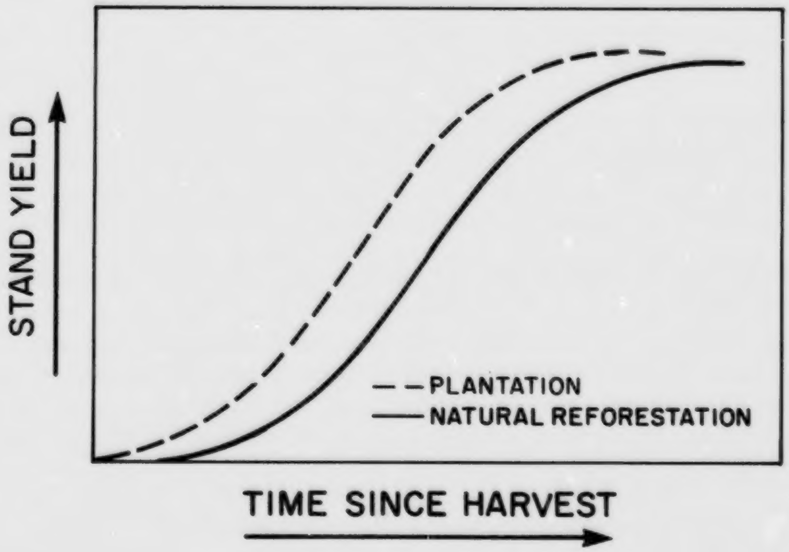

FIGURE 4. Average stand yield over time for successfully reforested plantations will generally be greater than the growth of natural stands because seedlings will be established sooner and stocking levels will be better controlled in plantations.

It may provide a mineral soil seedbed for germinants (Morris 1970; DeByle 1981), or temporarily control competing vegetation. The latter benefit will reduce the loss of water by interception and transpiration, thereby increasing the amount of water available to seedlings, which is stored in the soil during dry periods (Wells *et al.* 1979; Gaweda 1983). Broadcast-burned sites can also allow increased stocking of planted seedlings by improving planting access (Vyse and Muraro 1973).

Even when natural or direct seeding is used to reforest broadcast-burned sites, stand growth may be better than that in native forests because of the slowness with which large areas burned by wildfire become reforested. The effectiveness of natural seeding decreases with distance from the seed source (DeByle 1981). This distance may be prohibitively large following a wildfire, thereby allowing seral species to occupy the site first. These species will compete with germinants when they do become established, and reduce their growth.

Using broadcast burning as a site preparation practice to increase the success of artificial reforestation does not reduce its potential to impair long-term soil productivity, although the apparent site productivity has been increased. The increase is achieved by essentially shortening the rotation and achieving the maximum periodic annual increment sooner. Therefore, successful reforestation of sites amplifies the effects that broadcast burning has on soil productivity, because the stands will have to grow at or near maximum periodic annual increment earlier in the rotation, for a greater proportion of a rotation, and more often as the length of rotation decreases.

3.4 Competing Vegetation

A considerable amount of information is available on the effects of burning on vegetative cover and species composition (Dyrness 1973; DeByle 1981; Lotan *et al.* 1981) and on the autecological response of species (Feller 1982). This information provides valuable insight into the potential response to burning of established species and of other seral species which may invade the site after burning. However, these studies do not provide the information needed to determine how commercial species actually benefit from burning (or no burning) to control competing vegetation. In fact, for the commercially important species of the Pacific Northwest, there are virtually no published studies of the benefits of broadcast burning for controlling competing vegetation (Stewart *et al.* 1984). In the only study with several years of data (up to 16 years), Morris (1970) recorded some differences in vegetative cover between pairs of burned and unburned plots. Burning helped control a few species in the Oregon Cascades, such as *Rhododendron macrophyllum* G. Don. and *Gaultheria shallon* Pursh, but increased others, such as *Ceanothus velutinus* var. *velutinus* Dougl. ex Hook. and var. *laevigatus* T.& G. Natural stocking was higher on the burned plots in the early years along the Oregon Coast, but after 13 years there was no difference in stocking between burned and unburned plots in either the Coastal or Cascade sites.

In more recent studies in the Mixed Evergreen Forest Type of southwest Oregon, a site that was broadcast-burned in the spring and immediately planted with Douglas-fir seedlings had 28% higher survival than did the unburned sites after two summers (Steve Shade, Medford District, Bureau of Land Management, pers. comm.). On a similar type of site but with heavier brush, the brush was manually slashed, with half of the site then burned in early summer; Douglas-fir seedlings planted the following spring showed no differences in survival between the burn and no burn treatments, but seedling growth was significantly greater during the second and third years on plots that had been burned (unpublished data).

The most common benefit of broadcast burning, with respect to competing vegetation, is to reduce soil water use by the competing vegetation. This can significantly increase available soil moisture during dry periods (Gaweda 1983). Improved soil moisture should initially contribute to increased seedling survival and, depending on how quickly a site is revegetated, contribute to greater seedling growth for the first few years. On specific sites, burning to reduce vegetative cover can sometimes lower populations of small mammals which feed on young seedlings (Hooven and Black 1978).

The effectiveness of broadcast burning for controlling competing vegetation and, initially, increasing forest productivity is uncertain, based on these few examples. The observation common to all these studies, however, is that regardless of whether natural or artificial regeneration was used, the benefits of controlling competing vegetation are greatest when the time between burning and reforestation is shortest.

If broadcast burning increases the survival of seedlings and the growth of young stands, this should increase the yield of stands early in the rotation (Figure 5). The magnitude of this improvement will depend on how changes in the species cover and composition following broadcast burning have provided seedlings and young trees with a more favorable operational environment. Except for its initial effect on seedling survival, which can be a critical factor in site-specific situations, broadcast burning generally does not offer a lasting control of competing vegetation. Thus, a short-term improvement in seedling growth from vegetation control may be reduced or negated if the loss of nutrients during broadcast burning has reduced soil productivity. This would most likely limit stand yield later in the rotation when the stand reaches crown closure.

3.5 Stand Density

Broadcast burning also has the potential to affect forest productivity through its ability to alter stocking and stand density. The basic premise is that competition, whether from weed species affected by broadcast burning or from other trees regardless of species or size, changes the operational environment of the individual trees and stands. This can change the productivity of the site.

The scientific literature does not provide direct evidence that changes in stand density induced by broadcast burning affect productivity, although the potential of broadcast burning to affect initial survival on one site in southwest Oregon was mentioned earlier. However, studies of controlling competition, whether it is from weed species, excess stocking, or a combination of the two, clearly demonstrate the effect that differences in stand density of young plantations can have on productivity (Oliver 1984). Hall (1983) has also demonstrated the effect that stocking can have on basal area growth of older stands of similar site index.

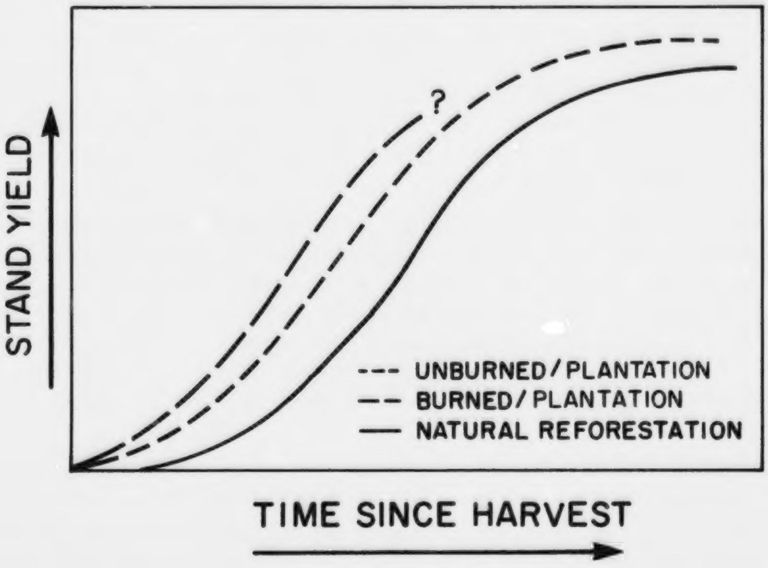

FIGURE 5. Controlling competing vegetation by broadcast burning may increase seedling survival and accelerate young stand growth, but the initial success may be lessened or negated by long-term effects of broadcast burning on soil productivity.

Although height growth is generally assumed to be insensitive to the effects of stand density (Lanner 1985), exceptions have been noted. Reukema (1979) reported that 53-year-old Douglas-fir trees were about 60% taller when planted at wider spacings (Figure 6). Most of this increase in height growth occurred after the trees were 29 years old. The potential for differences in stand density to affect site index as a measure of productivity may be greater on poorer sites; the site that Reukema (1979) studied was of site class IV, but King (1966) did not find site index of Douglas-fir on site class I lands to be affected by stand density.

Broadcast burning used for site preparation can affect stocking by changing seedling survival or vegetative competition at the start of a rotation. This establishes the possibility that the initial effects of broadcast burning may persist and affect stand density at some time later in the rotation. The higher the stocking, whether natural and/or planted, the more likely that productivity will be affected by stand density. Therefore, the ultimate effect that stand density changes induced by broadcast burning will have on forest productivity depends on how much the stocking of a site deviates from normal; the productivity of the site; and the likelihood that the site will receive future treatments, such as thinning, which can alter stand density significantly.

4 BROADCAST BURNING AND FOREST PRODUCTIVITY

Determining the effects that broadcast burning has on forest productivity is a complex problem because of fire's potential to affect several variables important to defining the operational environment of a species. Therefore, it is not unusual or unexpected to find contradictory data on the effects of broadcast burning on soil and site variables, competing vegetation, and establishment and growth of forest stands. These ambiguities have contributed to the uncertainty about the effects of broadcast burning on soil and

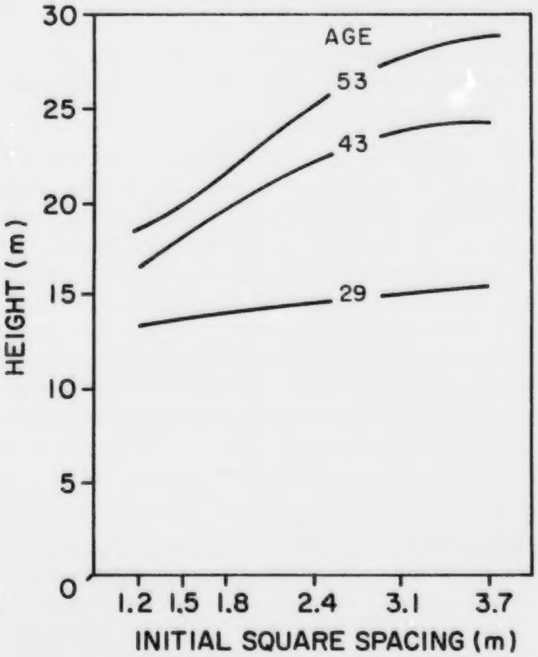

FIGURE 6. Differences in stand density, regardless of the reason, can sometimes affect forest productivity. In this example of planted seedlings on site IV land in southwest Washington, height of Douglas-fir is dependent on the initial spacing of the trees (Reukema 1979).

site productivity and emphasize the basic need for quantifying the effects that forestry activities have on the operational environment (McNabb and Campbell 1985).

Broadcast burning and artificial reforestation practices associated with intensive forest management can change or mitigate the operational factors that are most important to reforesting sites. Most changes in the operational environment are generally temporary, although they may greatly affect the survival and growth of germinants or small planted seedlings. This can have substantial effects on the apparent productivity of young plantations, but obscure the less obvious, long-term effects that broadcast burning can have on soil productivity.

Changes in reforestation success can have important long-term effects on site productivity because of the potential for site preparation practices to alter competition by other species and stand density. Thus, the short-term changes in the operational environment that aid successful reforestation of sites can have a long-term impact on site productivity, again confounding the effects that broadcast burning may have on soil productivity.

Broadcast burning can alter both forest soil and site productivity. Soil productivity is an integration of the effects that all the variables in the soil environment have on the growth of a specific species. In contrast, site productivity is an integration of the effects of all the variables in the forest ecosystem, including the soil environment, that influence growth. Thus, site productivity includes soil productivity. A forestry practice, such as broadcast burning, can affect one differently from the other. For example, a loss of nitrogen during broadcast burning may reduce soil productivity, but the control of competing vegetation may improve stand growth more than the loss of nitrogen reduced soil productivity. This could result in an absolute increase in site productivity, but the increase may be less than if a large loss of nitrogen had not reduced soil productivity.

Separating the effect that broadcast burning has on soil productivity from its effect on site productivity is important to understanding the effect of forestry practices on the long-term productivity of forests (McNabb and Campbell 1985). Soil productivity controls the maximum annual growth rate of stands, which is defined by a specific set of climatic, site, and stand conditions. As more silvicultural practices, such as thinning and fertilization are used to increase stand growth, soil productivity will become more important because it will limit forest growth on a specific site earlier in a rotation, for a longer portion of the rotation, and more often as rotations become shorter.

More research is needed to quantify the effects that broadcast burning has on the operational environment of a species throughout a rotation. These studies are necessary for both understanding the basic biological processes occurring in a forest and providing quantitative data for modeling growth. The establishment of permanent research installations for measuring growth over time is particularly important for validating growth models. Problems exist, however, as to what constitutes a control or reference stand for comparing growth on broadcast-burned sites. Therefore, documenting changes in the operational environment of all treatments is necessary for interpreting subsequent effects on site or soil productivity. Also of concern is whether the sequence and timing of the several forestry practices necessary to establish different treatments from a research perspective also change the operational environment from that common to the operational use of each treatment, i.e., the requirements of the study design also affect the differences in forest productivity that are measured.

Without further information, broadcast burning should be used with discretion on all sites. The consumption of a high proportion of the fuel and forest floor on a site is unacceptable, unless the resulting changes in the operational environment have been determined as necessary for the growth of young plantations. Most short-term gains in site productivity associated with intensive forest management can generally be achieved with low intensity broadcast burns or by other practices with less potential to damage soil productivity. A productive soil is the resource that foresters must manage to produce the forest products of the future.

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MASS WASTING IMPACTS TO FOREST LAND: FOREST MANAGEMENT IMPLICATIONS, QUEEN CHARLOTTE TIMBER SUPPLY AREA

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ABSTRACT

Mass wasting is a natural phenomena on the steep hillslopes of the Queen Charlotte Islands. A total of 236 failures greater than 400 m^2 was identified and mapped in clearcuts within the Rennell Sound inventory compartments. Failures disturbed 5.5% of the total clearcut land area; the largest percentage of land disturbed in one cutblock was 23%. The average failure was 0.6 ha in size and the largest recorded covered 6.9 ha. Seventy-five percent of slides were less than 0.5 ha in size and accounted for 33% of the disturbance. Slides greater than 0.5 ha in size involved 25% of failures and 67% of the disturbance. Failure rates expressed in terms of mapped slope stability hazard classes were 0.013/ha, 0.017/ha, 0.091/ha, 0.224/ha and 0.367/ha for classes I, II, III, IV and V, respectively. Unstable terrain (classes IV and V) occupied 15.6% of logged clearcuts, but slope failures generated from within this terrain accounted for 87% of the land disturbance. For every 100 ha of Class IV and V terrain logged, 20 ha and 30 ha, respectively, were disturbed downslope by mass wasting. A theoretical timber productivity loss based on inferences from the Rennell Sound study suggest that a non-recoverable land loss from mass wasting, if reflected over the short-term harvest, could result in a 15 165 m^3/yr reduction in the allowable annual cut — $3 million loss in annual economic activity derived from the Queen Charlotte Timber Supply Area.

1 INTRODUCTION

Mass wasting is a natural phenomenon on the steep terrain of the Queen Charlotte Islands. The term mass wasting encompasses a variety of slope movement processes by which masses of soil, rock and debris are transported downslope. Debris slides, avalanches and flows characteristically start on steep upper slopes; failure initially scours surficial materials 1-2 m deep and the rapid transport of materials downslope cuts a swath and destroys most vegetation along the slide path. A tangled deposit of mud and debris remains at the base of the slope (Figure 1). When a slide becomes confined in depressional channels and "V-notch" gullies, flows or torrents develop. Flows will travel for considerable distances over low slope angles, spreading debris along their paths (Wilford and Schwab 1982).

The rate of failure exhibited on the islands appears greater than in other localities along the British Columbia coast (Howes 1981; Chatwin and Rollerson 1983; Gimbarvesky [1987]; Rood 1984; Sidle *et al.* 1985; Rollerson 1984). The rate of failure is contributed to by the environmental and human factors prevalent on the Charlottes (Alley and Thomson 1978). Man's modification of forest terrain through logging leaves stability-sensitive slopes susceptible to failure for up to 20 years after clearcutting (Nakano 1971; Megahan *et al.* 1978; Ziemer 1981). The resultant mass wasting activity shows increases of 15 to 20 times the natural rate (Schwab 1983). Approximately 4% (or 46 ha) of the land on steep clearcut terrain in the Rennell Sound area was impacted by failures triggered during the 1978 rainstorm (Schwab

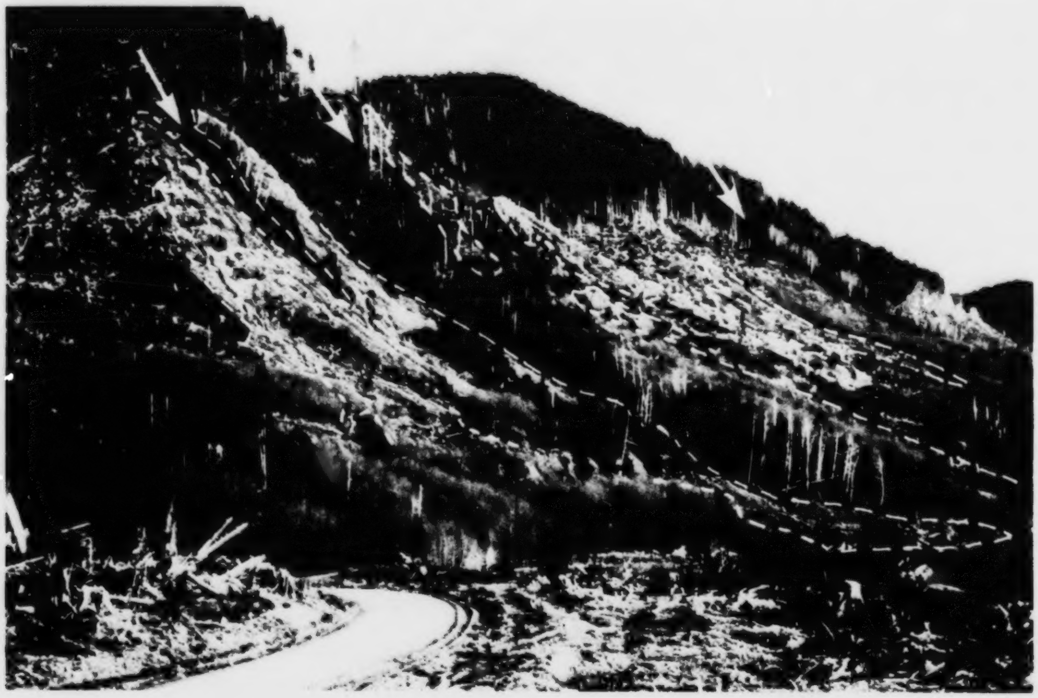

FIGURE 1. Debris avalanches in a clearcut. Note historic failures in relation to the more recent failures.

1983). Rood (1984) suggested that this storm may have triggered approximately 30% of the failures currently visible in clearcut terrain on the Queen Charlottes.

Mass wasting is the subject of considerable agency and public debate when human life is lost, property damaged and fish habitat destroyed. However, little emphasis is given to the on-site direct and indirect, short- and long-term impacts of mass wasting to forest site productivity. This paper, based on a field survey in the Rennell Sound area, discusses the implications of mass wasting impacts on long-term productivity and suggests the possibility of losses, which could affect the sustainable cut from the Queen Charlotte Timber Supply Area.

2 STUDY AREA DESCRIPTION

The Rennell Sound study area is located on the west coast of Graham Island, the major northern island of the Queen Charlotte Islands (Figure 2). The area encompasses Forest Service Inventory Compartments 25 and 28 of the Queen Charlotte Timber Supply Area (TSA) and covers a land area of 200 km^2. The productive forest land is 4670 ha with an average timber volume of 660 m^3/ha. Approximately 55% of the productive forest land was harvested by clearcut logging methods between 1968 and 1982. This area is representative of the environmental conditions in steep unstable watersheds in the Queen Charlotte TSA.

The bedrock geology of the Rennell Sound area has been described and mapped by Sutherland-Brown (1968). A thick accumulation of volcanic flows and pyroclastic rocks covers most of the area. Some sedimentary rocks, prophyrictic andesite, and volcanic sandstone are also present. Much of the area, except for a small area of plutonic rocks, is underlain with bedded limestone and argillite that outcrop

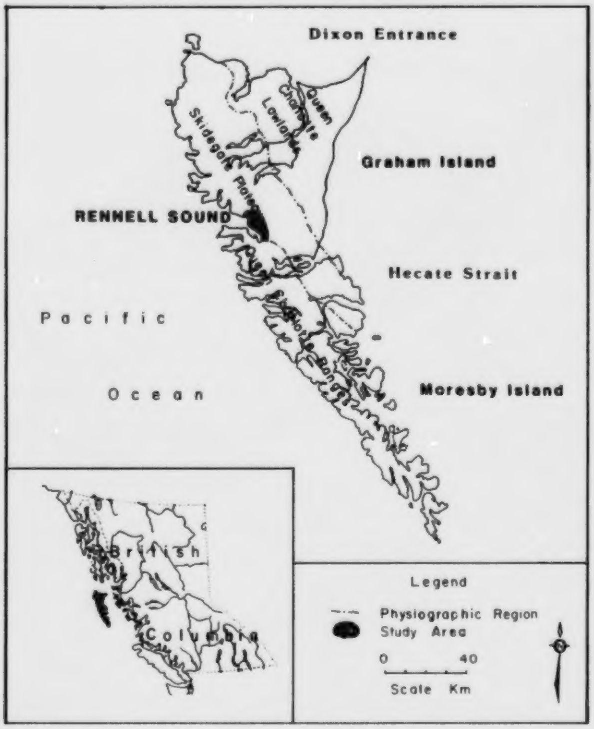

FIGURE 2. Rennell Sound study area located on the west coast of the Queen Charlotte Islands.

along the steep coastal shores of Shields Bay. The topography of the study area has been extensively modified by glaciation, and morainal deposits are located throughout. The morainal material has a clay loam to sandy loam texture, depending upon bedrock type and the degree of soil formation. Colluvium, the dominant surficial material, has a sandy loam to loamy sand texture (Alley and Thomson 1978).

The vegetation has been described by Banner *et al.* (1984) and falls within the Hypermaritime subzone (CWHd) of the Coastal Western Hemlock Biogeoclimatic Zone (Pojar *et al.* 1986). Stable terrain supports forest stands of western redcedar (*Thuja plicata*), yellow-cedar (*Chamaecyparis nootkatensis*), shore pine (*Pinus contorta*), and western hemlock (*Tsuga heterophylla*). The soils are organic, developed on a saprolite veneer over bedrock, or Humic Podsols developed over till. Unstable hillslopes support productive stands of Sitka spruce (*Picea sitchensis*) and western hemlock. Alder (*Alnus rubra*) is often a component of the more recently active slopes, while hemlock and cedar are more dominant on slopes that have not been recently active. The soils, depending upon their state of development, are regosolic, brunisolic, or podzolic, developed on colluvial veneers, fans, and aprons. Buried soil horizons often occur on the lower slopes. The rooting depth of all tree species is shallow, seldom extending below 30 cm into the mineral soil on well-drained sites, or below 15 cm on more poorly drained sites. The majority of roots are confined to surface organic soil horizons.

The average annual precipitation within the Rennell Sound Study area ranges from 2300 mm at sea level (Gospel Point Station) to values in excess of 4000 mm in locations of more significant topographic barriers (more representative values are 4169 mm at Sewell Inlet and 4218 mm at Tasu Sound). Rainstorms known to have triggered mass wasting along the eastern shores of Rennell Sound have occurred almost annually over the past 10 years (Table 1). Areas of intense precipitation or storm cells probably contribute to the localized occurrence of failures found even within the Rennell Sound area after major storms.

Clearcut areas in the study have all experienced intense rainfall sufficient to trigger mass wasting. The occurrence of failure (Schwab 1983) appears to fall within the 4- to 15-year period following clearcutting, which is considered to be the time period of minimum slope stability after clearcutting (Ziemer 1981).

3 METHODS

The extent of mass wasting impacts on clearcut forest land was quantified through an inventory of all cutblocks (2498 ha) within the Rennell Sound inventory compartments 25 and 28. This inventory included only slope failures that disturbed an area greater than 400 m^2 in clearcuts, and that are visible on 1:10 000 (1982) black and white aerial photography. The slide disturbance information was then plotted by zoom transfer scope onto 1:10 000 topographic maps. All data were tabulated by cutblock. A helicopter flight over the area in October 1985 enabled identification of failures that occurred since the photography was flown. Cutblocks that exhibited recent failures were photographed with a 35 mm camera. These additional failures were plotted by hand onto the 1:10 000 topographic base maps. A detailed examination of failure origin, frequency and size was done by slope stability hazard class for the 22 clearcuts (1498 ha) which were previously terrain-mapped at a scale of 1:20 000.

TABLE 1. Rainstorms known to have triggered mass wasting within the Rennell Sound study area

Storm Occurrence	Total Precipitation (mm)	Storm Duration (days)[c]
Oct., 1974[a]	475	3
Oct., 1975	243	3
Nov., 1976	198	3
Oct., 1978[a]	278	3
Jan., 1984[a]	154	5
Feb., 1985	181	3
Sept., 1985	171[b]	1

[a] Queen Charlotte-wide events.

[b] Total precipitation estimate.

[c] Duration of rainfall that triggered failure.

4 RESULTS

A total of 236 mass movements greater than 400 m^2 were identified and mapped within the Rennell Sound clearcut units; of these, 12% were road related.[1] The total area disturbed by failures was 137 ha or 5.5% of the total clearcut area. The largest percentage of land area disturbed in a single cutblock was 23%. The average failure size was 0.6 ha and the largest recorded covered 6.9 ha. Slide frequency by size class (Figure 3) and the portion of disturbed land area by size class (Figure 4) showed a strongly skewed distribution with a high frequency of small (low magnitude) failures and a low frequency of large failures. Seventy-five percent of the slides were less than 0.5 ha in size, but accounted for 33% of the

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[1] The lower slide area limit of 400 m^2 eliminates the many small road-associated and clearcut failures difficult to map from air photographs.

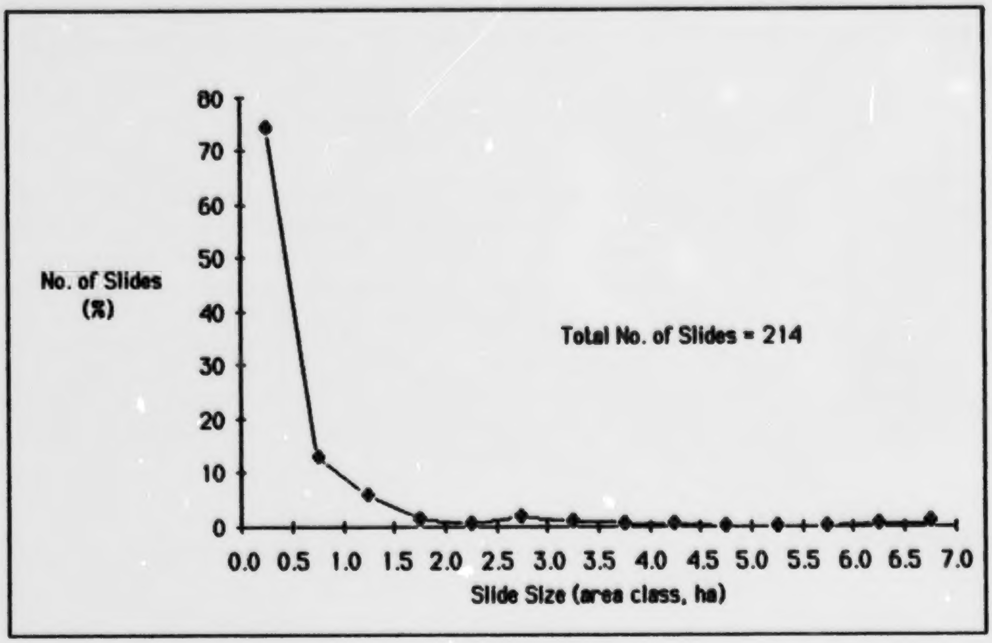

FIGURE 3. Slide frequency by size class.

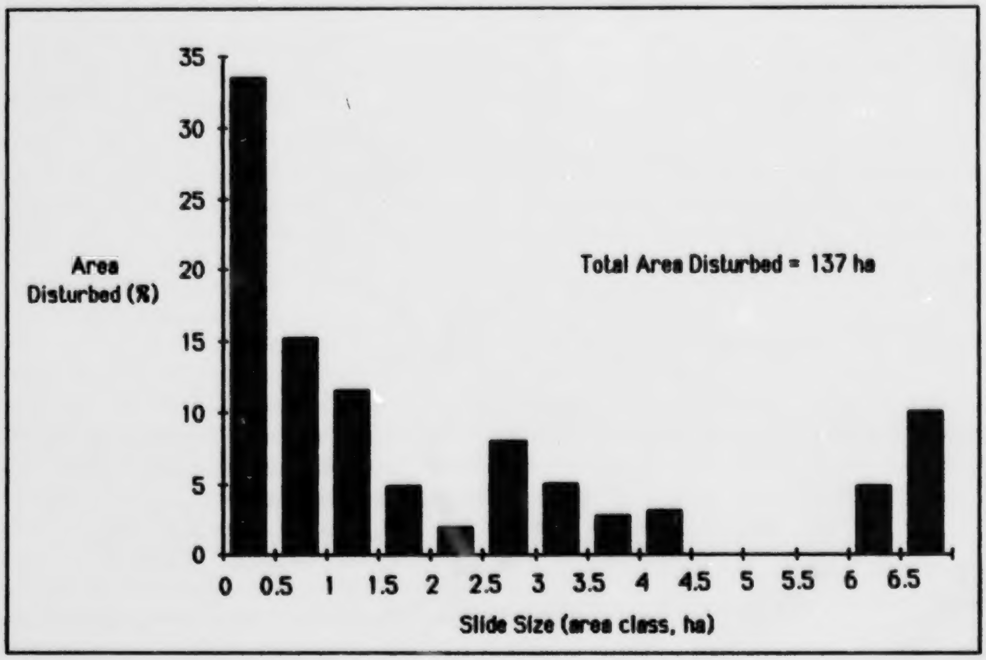

FIGURE 4. Clearcut land area disturbed by failure size class.

land disturbance; slides greater than 0.5 ha in size involved 25% of the failures and disturbed 67% of the land area. Three of the largest failures accounted for 15% (or 20 ha) of the slide disturbance.

Slope failures within clearcuts average 0.10 failure per hectare (10 failures/km^2 of logged land). However, failure rate, if expressed in terms of the slope stability hazard classes (Table 2) mapped at a scale of 1:20000 for the study area, shows interesting results (Figure 5). Failure frequency was 0.013/ha, 0.017/ha, 0.091/ha, 0.224/ha and 0.367/ha for slope stability hazard classes I, II, III, IV, and V, respectively.

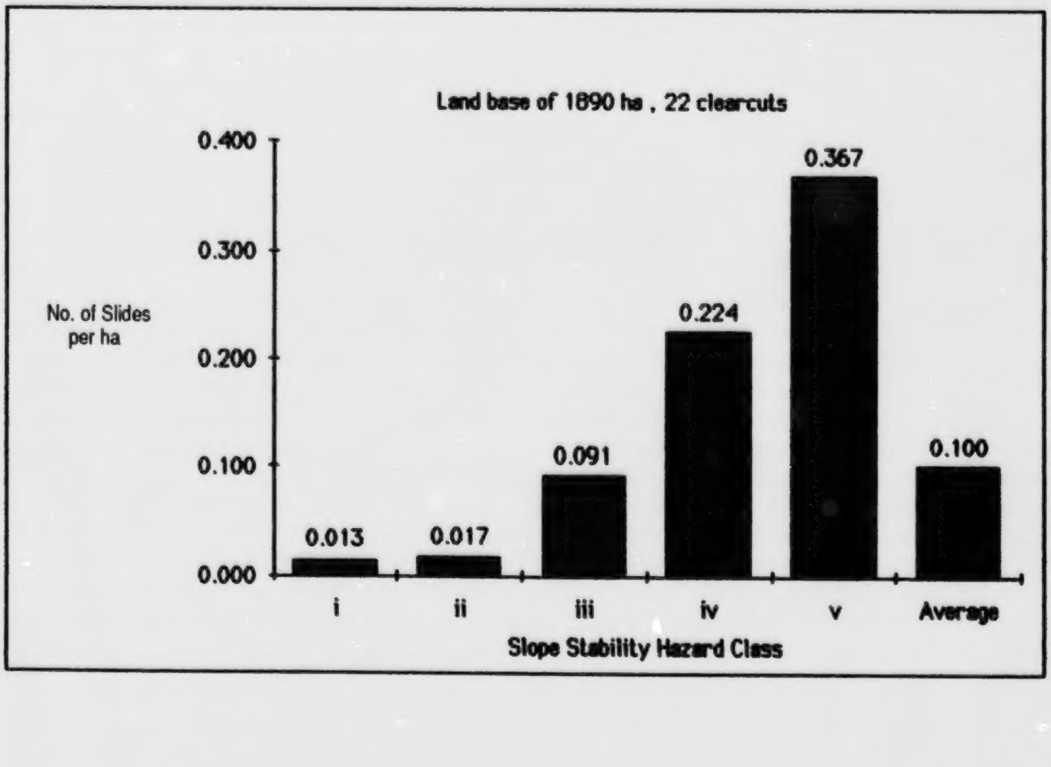

FIGURE 5. Slope failure frequency by slope stability hazard class.

TABLE 2. Slope stability hazard classes, Rennell Sound[a]

Class	Natural Stability	Description	Management Interpretation
V	Active	Terrain units associated with recurrent natural mass movement - active landslide units - reforested landslides - steep gullied units with distinct fan deposits	Protection forest (ES1)[b]
IV	High Potential	Terrain units with similar geological characteristics to Class V, but lack evidence of previous large or frequent mass movement	Some harvesting and major road induced instability (ES2)[b]
III	Low Potential	Sensitive microsites, low gradient gullies and seepage areas. Units above and below Class IV and V units	Road on- and off-site induced instability
II	Stable	Minor inclusion of sensitive microsites	Minor road on-site induced instability
I	Stable	No evident sensitive sites	

[a] Slope stability hazard classes derived from data on surficial material soil moisture, hillslope morphology, and slope gradient. Interpretations are based on a subjective assessment. Rennell Sound terrain map prepared by R.Townshend (1979, Geotechnic report, Rennell Sound, Queen Charlotte Islands, B.C. Min. For., unpubl. report); hazard map revisions in 1983 by Townshend and Schwab.

[b] Identified areas of actual (ES1) or potential (ES2) erosion; classification described in the B.C. Ministry of Forests' Forest Inventory Manual, Chapter 2, Environmentally Sensitive Areas (1984).

Stability-sensitive terrain occupies 15.6% of logged clearcuts (Class IV and V). However, the larger slope failures generally originated from within these high slope stability hazard classes and accounted for 87% of the disturbed land. For every 100 ha logged in a stability class, land impacts downslope were 0.07 ha, 0.5 ha, 3.1 ha, 20.6 ha and 30.3 ha for the slope stability hazard classes I, II, III, IV, and V, respectively (Figure 6). In essence, stability hazard classes that show active slope failure (Class IV) before logging, produced the largest downslope impacts after the terrain was logged.

Mass wasting from clearly identified unstable terrain in clearcuts, expressed as percent area in unstable terrain and percent area disturbed in a clearcut, is presented in Figure 7. The relationship is significant (95% confidence level, n = 22), indicating that the percent area of a cutblock disturbed by failures originating in unstable terrain was directly related to the percent of the cutblock in unstable terrain. In other words, for every 100 ha of hazard classes IV and V logged, 25 ha was disturbed by mass wasting that originated from within the unstable terrain.[2] However, land area disturbance from failures was substantially reduced in cutblocks where a direct management decision was made to avoid logging on clearly identified unstable terrain.[3] To illustrate this point, two blocks were located sequentially along a valley side. Block one was engineered and logged with no recognition of potential slope stability problems. The land area disturbed in this block by failures originating from the unstable terrain approached the land area of the unstable terrain harvested (8.4 ha unstable; 6.5 ha disturbed by slides). Detailed ground inspection of the second block identified the potential failure zones. A management decision to harvest some unstable land but not the identified failure zones produced a substantial reduction in land area disturbed by failures (20.5 ha unstable; 1.5 ha disturbed by slides).

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[2] The land area disturbed would probably be much greater if harvesting was permitted on extremely sensitive terrain currently removed from the productive operable forest land base in the Rennell Sound Inventory Compartments.

[3] The effect of not harvesting highly unstable zones on a slope would reduce the total land area disturbance by slides from 5.5% to approximately 1%.

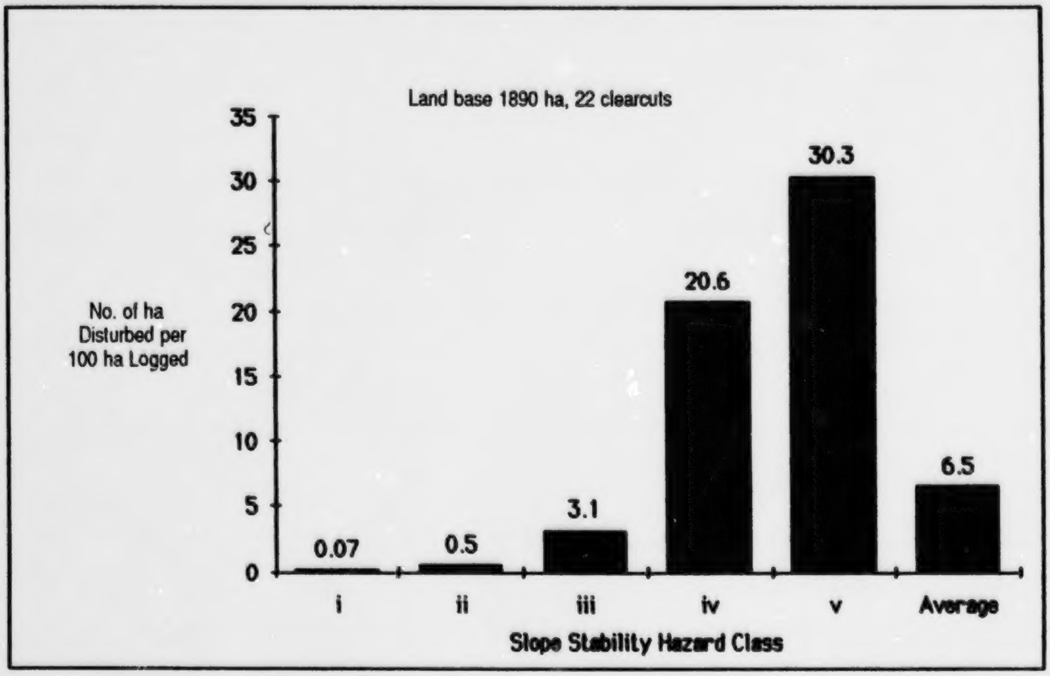

FIGURE 6. Land area disturbed by failures originating from within mapped slope stability hazard classes.

5 FOREST MANAGEMENT IMPLICATIONS

Many productive forest sites in the Rennell Sound area owe their existence to a history of geomorphic processes such as mass wasting and subsequent fluvial deposition. Natural mass wasting events are widely distributed in both time and space and, therefore, do not cause widespread destruction; rather, they serve to maintain soils capable of supporting productive forests. Forest harvesting on steep, unstable hillslopes does, however, increase the rate of mass wasting (Schwab 1983), which can result in large-scale negative impacts to forest land productivity. Smith *et al.* (1986) estimated a productivity loss on slides of 70% in the first 60 years and in the order of 50% at the end of a 80-year rotation. A gradual productivity recovery on slides is expected in subsequent rotations. Land areas covered with large failures, or intensively stripped with smaller failures, will probably require a doubling of the rotation age (160 years). Small failures and areas with a low frequency of failure would likely be cut at the time adjacent stands of timber are harvested; however, volume would be low or piece size too small for economic use.

The on-site productivity impacts of mass wasting generally receive little emphasis compared to off-site impacts (roads, personal property, human life). However, there are both short- and long-term direct and indirect consequences associated with mass wasting impacts to forest land.

The direct cost of mass wasting is realized when slides cut a swath through second-growth forests. A loss in stand investment could approach $1700/ha (Table 3). These losses include: plantation establishment, silvicultural surveys, brushing and weeding, and juvenile spacing costs. Theoretically, a comparable investment could be made to restore a forest crop to these sites. However, such investments are questionable in light of the productivity decline. In addition to actual productivity impacts, the loss of

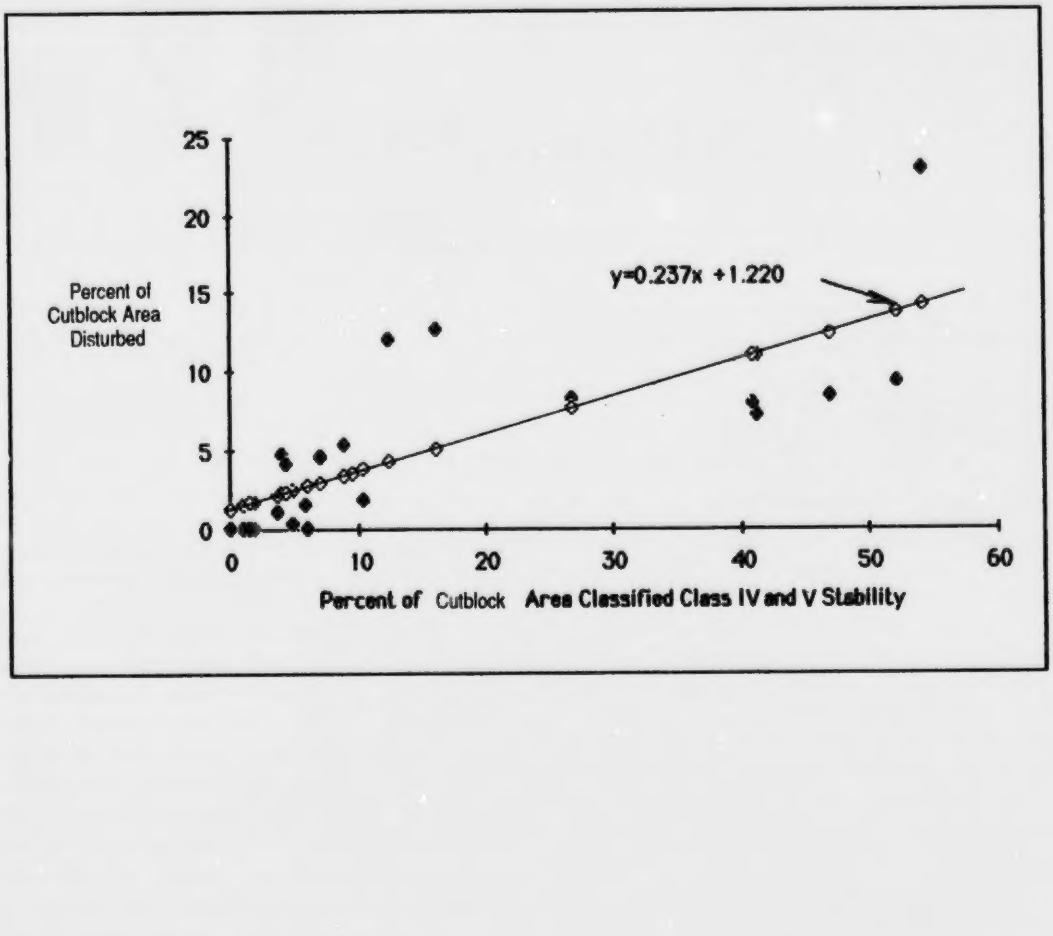

FIGURE 7. Relation between steep, unstable slopes and area of cutblock disturbed.

second-growth stands is viewed as extending the regeneration delay by the period of time equivalent to the age of the destroyed second-growth stand. This loss is substantial, particularly on highly productive lands that could be managed for timber production on a 40-year rotation (MAI 9-15 m^3/ha per year).

TABLE 3. Silvicultural investments in second-growth forests

Silviculture Value	Cost[a] ($/ha)
Plantation establishment	250
Silviculture surveys	10
Brushing and weeding	650
Juvenile spacing	800
TOTAL	1710

[a] Average costs for the Rennell Sound area (Source: Pers. Comm., 1985. B.C. Forest Service, District Office, Queen Charlotte City).

Mass wasting impacts to forest land productivity may hold a large future indirect cost. Let us assume the worst case senarios that can result in accelerated failure rates: no recognition of unstable terrain in forest land planning; no planned application of alternative harvesting systems on sensitive terrain; no road maintenance of inactive forest roads and abandoned roads not being put to bed; and no slide rehabilitation. This would result in a non-recoverable land loss from mass wasting which could be deducted from the projected timber yield. The present land disturbance from mass wasting in the Rennell Sound area could thus reflect a theoretical timber production loss of 1233 m^3/yr, representing 98 640 m^3 at rotation, with an estimated stumpage value of $900 000 and a possible economic value of $19.7 million (Table 4). Timber production value losses, if projected over the complete harvest of the mature operable forest land within the Queen Charlotte TSA could thus approach 1.25×10^6 m^3, with an estimated present stumpage value of $11.3 million and economic value of $242 million. A sustained long-term productivity loss, if reflected in current harvest levels, could thus result in a 15 165 m^3/yr reduction in the allowable annual cut - a $3 million dollar annual loss in economic activity derived from the Queen Charlotte TSA. A gradual productivity recovery expected on slides could offset this theoretical annual loss in yield, but only if re-entry onto potentially unstable slopes during subsequent cutting rotations does not initiate more slides.

A recognition of the negative consequences of slope failure is necessary when logging pushes into potentially unstable terrain. As already stated, the cost of poor logging practice could be substantial. Logged unstable hillslopes contributed to the majority of forest land disturbance in the Rennell Sound area, generally to more productive sites downslope. Judging from these experienced failure rates, where stability problems were not recognized prior to logging, the rates expected from failures originating in unstable terrain (Class V) could affect up to 30 ha of every 100 ha logged. The removal of these extremely unstable slopes from the net operable land area is thus justified, based on a public preception of forest site loss; this does not include the cost of other disincentives, such as the risk to human life, private property, and aquatic environments. Approximately 45 000 ha are currently removed from the operable land base because of these stability concerns. Proven good management practices, however, using alternative logging and silvicultural systems on unstable terrain, could make available for harvest various large land areas presently not contributing to the cut.

Forest land practices must be sensitive to slope processes and the resultant negative consequences, so that mass wasting on potentially unstable terrain can be recognized, prevented and controlled. Otherwise, there will be a continual erosion of the productive forest land base. Where, in spite of our best efforts, we fail to avoid or prevent mass wasting, management efforts should focus on mitigation and rehabilitation of land and water resources.

TABLE 4. Projected productivity and economic activity losses from mass wasting for the Queen Charlotte TSA

Land Unit	Land Area (ha)	Land Disturbance by Mass Wasting (%)	Land Disturbance by Mass Wasting (ha)	Loss MAI[a] @ 9m^3/yr (m^3/yr)	Loss Stumpage[b] Rotation 80 yr \$9.10 /m^3 (\$ million)	Loss Log[c] Market Value @ \$85/m^3 (\$ million)	Loss Economic Activity[d] Annual \$200/m^3/yr (\$ million)	Loss Economic Activity[d] Rotation 80 yr 200/m^3 (\$ million)
Rennell Sound Detailed Study[e]	1498	6.5	123	–	–	–	–	–
Rennell Sound Current Cutover	2498	5.5	137	1233[f]	0.9	8.4	0.25	19.7[g]
Queen Charlotte TSA Projected								
Stable	40 000[h]	1.4	560[f]	15 165[f,i]	11.0[f]	103.1[f]	3.0[f]	242.6[f,g]
Unstable	4500[h]	25	1125[f]					

[a] Mean Annual Increment (MAI) based on B.C. Forest Service volume/age curves for spruce hemlock types, medium site, Forest Inventory Zone A. Values could be as high as 15 m^3/ha, Western Forest Products (1985, Productivity of major ecological associations of Tree Farm licence 24, Queen Charlotte Islands, unpubl. report).

[b] Stumpage rate, 1975-1982, averaged for all species, Rennell Sound Cutting Permits.

[c] Log market value, 1975-1982, averaged for all species, Rennell Sound Cutting Permits.

[d] Value of \$200 m^3 based on the value of gross economic activity generated by harvesting 1 m^3 of wood, 1984 dollars (direct \$115/m^3 and indirect \$85/m^3). Source A.B.C.P.F. (1985).

[e] Clearcut land covered by 1:20 000 terrain hazard maps.

[f] Projection based on the Rennell Sound study.

[g] Value of sawlog timber not available at the time of liquidation, 1984 dollars.

[h] Estimate for the Queen Charlotte TSA; 40 000 ha of mature timber on relatively stable land (Class I, II, III), and a 10% contribution (4500 ha) from unstable lands (Class IV and V). Source: B.C. Ministry of Forests (1982 and 1983).

[i] Volume loss 100% based on the complete removal of the cut for one rotation because of low volumes and small piece sizes. Volume may be available for harvest after two rotations.

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SESSION 2 SYSTEMS ANALYSIS APPROACH USING FORCYTE

LONG-TERM IMPACTS OF FOREST MANAGEMENT ON SOIL FERTILITY AND FOREST PRODUCTIVITY: A SYSTEMS ANALYSIS APPROACH USING FORCYTE

J.P. Kimmins[1], K.A. Scoullar[2] and L. Chatarpaul[3]

ABSTRACT

Increasing the intensity of forest management on a shrinking land base, together with the effects of acid rain and atmospheric warming (the "greenhouse" effect), will alter the nature of the soil and atmospheric environments in which forest crops are grown in the future. This in turn will reduce the accuracy of traditional "historical bioassay" forest yield predictors. The use of process simulation models to predict future forest yield and the site consequences of these management and environmental changes is theoretically sound, but has several limitations.

A hybrid simulation approach to forest yield prediction, combining both the historical bioassay and the process simulation approaches, is described in this paper, and an example, FORCYTE-11, is discussed. This model, which has been used in 11 countries for teaching, research and management gaming, could potentially be developed for use in conjunction with research into land reclamation activities, agriculture, "acid rain" and the "greenhouse effect".

1 INTRODUCTION

Soil contributes a variety of important values to human society, including its role in regulating the regimen and quality of water, and in providing physical anchorage and the essential resources of moisture and nutrients for plant growth. Soil degradation threatens to lower these values, and it may change the site productivity relationships that lie at the heart of our traditional approaches to predicting forest and agricultural site productivity. The ability to make accurate predictions about future crop production is important in both agriculture and forestry because investment and other management decisions require accurate information about the yield that can be expected from alternative investment and management strategies. Resource management planning requires that we be able to predict the medium-and long-term consequences of our management activities, as well as the short-term consequences.

Traditionally, yield prediction in both agriculture and forestry has been based on an "historical bioassay" (HB) — the record of past crop yield on the site in question (Kimmins 1985, 1986; Kimmins *et al.* 1986). This has generally been a very satisfactory approach because it is not limited by our still imperfect understanding of soil, microclimatic and plant physiological processes, nor by our ability to gain knowledge that is currently lacking. In forestry, the HB approach has the added advantage of integrating the effects on growth of all the factors of a particular site over the entire rotation, which usually involves many decades, or even centuries. However, the HB approach is limited to those growth conditions that pertained during the period when the historical bioassay was established. It cannot, on its own, make reasonable predictions for futures in which the soil and/or atmospheric resource have been changed in

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ways that affect tree growth. Consequently, soil degradation or improvement may invalidate our traditional HB methods of yield prediction, as may human-induced climatic change.

One alternative to historical bioassay yield prediction is the process simulation approach, e.g., Barclay and Hall (1986) and papers in Agren (1986). Theoretically, if we could simulate all of the processes that determine plant growth and mortality over the crop production perido, we could accurately predict yield for a wide variety of potential future plant growth environments. However, the process simulation approach to simulating forest growth and the response of forest ecosystems to a wide range of management practices has not produced any generally applicable yield predictors to date. Such models have enormous value as teaching and research tools to integrate accumulating knowledge about how ecosystems work, to identify knowledge gaps, to generate hypotheses for testing, and to be the basis for developing research strategies. However, they tend to lack portability, to be extremely demanding of calibration data, to be too complex for the average scientist to understand and for the average resource manager to use, and to be too demanding of computational power (although this is rapidly becoming less of a consideration). They are also limited by our incomplete understanding of many ecological processes. Most process models refer to ecological processes at spatial and temporal scales that are different from the phenomena being predicted: individual plants or parts of plants rather than whole stands of trees, and processes on a daily or weekly time scale, rather than the decades or centuries required to grow one or several tree crops (Fig. 1). This can lead to erroneous predictions. For example, soil organic matter or nitrogen depletion that may appear to be unacceptable on a 10- to 20-year time scale may not be so important over a rotation because of natural or human-related replacements (see arguments in Kimmins 1977). Conversely, improved soil nutrient availability and tree growth over a 10- to 20-year post-harvest period as a result of intensive site preparation treatments may be associated with an overall rotation-length decline in site fertility and growth on some sites (e.g., Lundmark 1977; Squire 1983; Farrell 1984; Raison 1984).

The objective of this paper is to introduce the reader to an example of a second "hybrid simulation" alternative to the HB approach to yield prediction: FORCYTE. The hybrid simulation approach shares with the process approach the advantage of increased flexibility and the ability to predict yield under changed future growing conditions (particularly altered soil conditions), but it avoids to some extent the difficulties that a process approach has in dealing with the problems of ecosystem complexity. A brief introduction to the 11th version of this model is given.

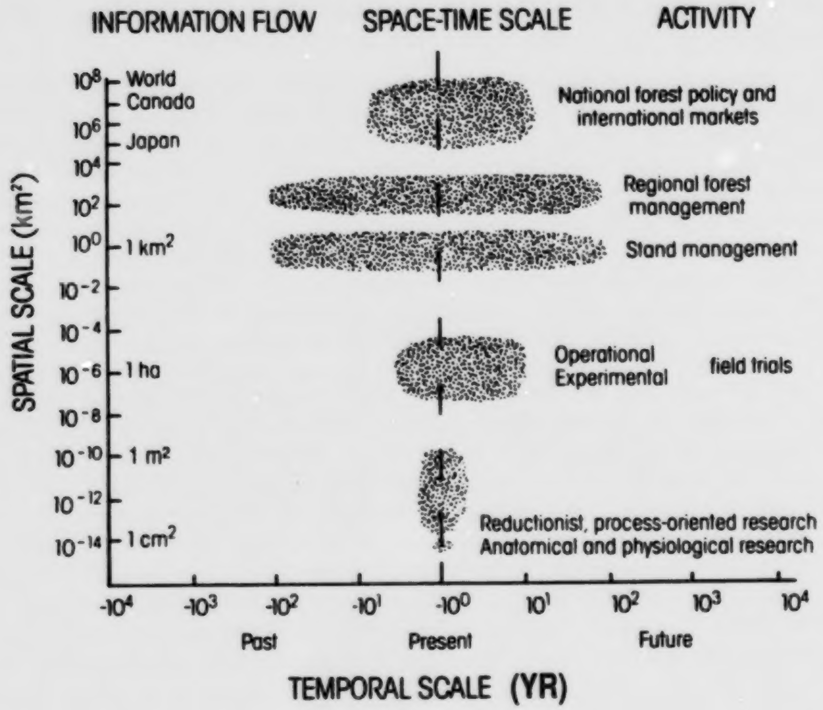
INFORMATION FLOW
SPACE-TIME SCALE
ACTIVITY
SPATIAL SCALE (km²)
10⁸
World
Canada
10⁶
Japan
10⁴
10²
10⁰
1 km²
10⁻²
10⁻⁴
10⁻⁶
1 ha
10⁻⁸
10⁻¹⁰
1 m²
10⁻¹²
10⁻¹⁴
1 cm²
National forest policy and international markets
Regional forest management
Stand management
Operational
Experimental
field trials
Reductionist, process-oriented research
Anatomical and physiological research
-10⁴
-10³
-10²
-10¹
-10⁰
10¹
10²
10³
10⁴
Past
Present
Future
TEMPORAL SCALE (YR)

FIGURE 1. Variation in the temporal and spatial scales associated with different levels of forestry activity, from reductionist forest research up to national forest policy (based on Baskerville 1986; used with permission).

2 THE HYBRID SIMULATION APPROACH AND ITS ROLE IN PREDICTING THE EFFECTS OF SOIL DEGRADATION ON SITE PRODUCTIVITY

The hybrid simulation approach to predicting future site productivity involves the combination of an historical bioassay of the past site growth potential and the simulation of certain growth-determining processes. The processes to be simulated are those that are believed to be most subject to alteration in the types of future growth environments you wish to consider. For example, in order to answer questions concerning the growth environments accompanying shorter rotations, more complete biomass utilization, alternating crop species rotations, species mixtures, various fertilizer regimes, and intensive post-harvest site preparation, it is necessary to simulate the soil processes that determine soil nutrient availability, canopy architecture, and competition for nutrients and light. The important growth-determining processes of regional climate, slope position, soil depth, and soil coarse fragment content are not altered as the above management parameters are changed, except in the possible case of serious soil erosion when the latter two parameters may change. The effects of these parameters are implicit in the historical bioassay and need not be simulated unless there are important factor interactions that must be considered. Soil moisture conditions may be altered, but probably less so than light and nutrient conditions. On the other hand, if you wish to investigate the possible effects of climatic change on forest growth and on the economic viability of the intensification of forest management, a simulation of the effect of climatic variables must be included.

The hybrid simulation approach uses the simulation of ecological processes to assess whether the yield trends predicted by the historical bioassay will be achieved, exceeded or not met under a variety of future management scenarios. Conventional yield table or mensurational yield model predictors generally give the same yield prediction irrespective of whether a site has experienced severe summer fire, soil compaction, or soil erosion (which may result in a reduction of productivity), or whether site preparation has improved soil temperature conditions and mineralization (e.g., in an acid raw humus forest floor). The hybrid approach permits us to harness the accumulated knowledge of soil processes and plant-soil interactions into an assessment of the effects on future forest productivity of management-related impacts on soils.

2.1 Introduction to FORCYTE-11[1]

FORCYTE-11 is a modelling framework rather than a specific model. It can be calibrated as an ecosystem-level management model with which to examine the short-, medium- and long-term consequences of a wide variety of crop or land management practices. These include conventional even-aged, clearcut-harvested, monoculture or mixed species tree crops, or tree crop rotation sequences (sequences of different species each of which is grown as a monoculture); agroforestry systems involving food crop/tree crop rotation sequences, or interplanting of food crops into plantations of trees; conventional agriculture cropping systems (monoculture, mixtures, or crop rotation sequences); and land reclamation (prediction of rate of vegetation development, fertilizer needs, etc., for the revegetation of mined or otherwise disturbed land). The model can be calibrated for short-rotation or long-rotation crops, from the tropics to the subarctic.

When calibrated appropriately, FORCYTE-11 simulates the secondary plant succession of the forest stand cycle, from pioneer (herbs or shrubs) through seral (e.g., deciduous hardwoods), to sub-climax or climax tree species (e.g., conifers). Plant growth and biomass turnover are simulated on the basis of input data that define: the biomass accumulation in each biomass component of each plant species over time; the age-class structure of biomass components (e.g., number of years of leaf retention, the length of the live crown, the number of years (rings) of sapwood, fine root turnover rate); the photosynthetic adaptations of the foliage (photosynthetic light saturation curves); and the stand density and distribution of stem sizes over time (a stand table). Data on concentrations of up to five nutrients in each biomass component, and on foliar leaching relationships, permit the simulation of nutrient uptake, distribution in the plant, internal cycling, and loss to litterfall, reproduction and foliar leaching.

Data are required for each species growing in monoculture. If data are given for several different sites that vary in nutritional status, the model is able to simulate the change in growth strategy (root/shoot ratio, fine root turnover, tissue chemistry, enternal cycling) of plants in response to management-induced changes in soil nutrient availability. If data are given for only one site, the model simulates changes in growth according to simulated nutrient availability (described below), but does not alter plant growth strategy.

FORCYTE-11 simulates plant growth by calculating, from the mainly inventory-type data plus some process-type data described above, an index of foliage production efficiency (kilograms of biomass produced per kilograms of foliage, corrected for the simulated shading) for each species. This becomes the driving function for simulated plant growth, subject to the simulated availability of nutrients. FORCYTE-11 thus extracts from a set of mainly empirical data on biomass accumulation and turnover, measures of the rates of various ecophysiological and plant population processes, thereby obviating the need for the expensive and time-consuming direct measurement of these process rates.

In its 11th version, FORCYTE grows plants according to simulated nutrient availability and canopy light conditions, and simulated competition for these resources. The important effect of the availability of soil moisture is implicit in the model's driving function, but because of the importance of competition for moisture, and because some management practices may alter soil moisture status, an explicit treatment of moisture will be added to the 12th version of the model.

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[1] FORest nutrient Cycling and Yield Trend Evaluator: 11th version. Only a brief introduction is given here. For more details, see Comeau and Kimmins (1986), Kimmins (1986), Kimmins *et al.* (1986), Kimmins and Scoullar (1987), and Kimmins and Sollins (in press).

2.2 Soil Processes Represented In FORCYTE-11

The genesis of the FORCYTE series of models was concern over the depletion of soil fertility that may accompany the intensification of forest management. The earlier versions of the model (up to FORCYTE-10) focussed entirely on simulated nutrient availability as the major site variable limiting growth. Although canopy light conditions have been added in FORCYTE-11, soil conditions remain the central focus of the model.

FORCYTE-11 consists of three major compartments (Fig. 2): a plant compartment (plant biomass by species and biomass component, and the nutrient content by soil "layer" [e.g., a forest floor, one or several user-defined layers of mineral soil] and soil nutrient exchange capacities); and an "available soil nutrients" compartment. The latter is not related directly to any conventional analytical measure of soil nutrient availability, but is simulated in the model as the balance between a variety of inputs and outputs to and from this compartment.

Plant biomass and the nutrients contained therein are transferred to the soil via the natural processes of plant death (due to competition, defoliation or fire), above-ground litterfall, and root death. Simulated management treatments such as spacing, thinning, pruning and final harvest also result in such transfers. Wind effects are not represented explicitly, but can be represented in terms of the other management treatments (e.g., canopy tatter or stem break can be called a "natural pruning"; windthrow a "natural thinning").

Dead organic matter transferred to the soil compartment undergoes decomposition, in which both immobilization and mineralization can be simulated. This is done on the basis of input data on substrate-specific weight-loss rates and changes in nutrient concentrations as materials proceed from fresh litter through various stages of decomposition to humus (empirical field data). Immobilization results in the transfer from "Available Soil Nutrients" back to the SOIL compartment; mineralization results in the reverse.

Materials can be lost from the SOIL compartment by simulated fire or litter raking (harvesting logging slash and/or ectorganic layers), or by erosion. Organic matter can be transferred from one soil layer to another by simulated soil stirring (there is a subroutine that simulates soil mixing by soil animals) or ploughing. The effects of soil compaction can be simulated in terms of the proportion of the soil volume (and the resources contained therein), by layer, which is temporarily made unavailable to plant roots by soil compaction, and the rate at which this compacted soil volume is returned to active plant use.

Once soil nutrients have been transferred to an "available" form, they can be taken up by plants (controlled by the simulated plant uptake demand), leached to a lower soil layer, removed in eroded materials, returned to the SOIL compartment by immobilization, temporarily held on soil exchange sites, or more "permanently" held (e.g., phosphorus) on sorption sites. It is intended that denitrification should also be represented, but this simulation is not currently operational. The Available Soil Nutrients compartment receives nutrients by mineralization (from SOIL), by fire (from PLANTS or SOIL), by foliar leaching (from PLANTS), or by fertilization, slope seepage, mineral weathering, and precipitation (these four rates are defined in the input file).

Biological fixation of nitrogen is represented both as an addition to the PLANT compartment (by symbiotic fixation, the nitrogen being added directly to the fixing species) and as an addition to the SOIL compartment (by nonsymbiotic fixation, the added nitrogen being available to provide for increases in N content of decomposing organic matter).

The simulation of soil leaching is based upon simulated nutrient availability for leaching, soil occupancy by roots, plant nutrient uptake demand, and soil exchange capacities (given in the input file for mineral soil and decomposing organic matter separately; both AEC and CEC are simulated). The simulation assumes that if the "availability" of nutrients exceeds both the ability of the plants to take them up and the site's unused soil exchange capacity for those nutrients, the nutrients will be leached. It is recognized that this is a very imperfect representation of what is in reality a very complex process. However, it is based on the belief that omission of an important process from a simulation model can result in as large or larger an error in the predictions of the model than inclusion of a conservative representation of that process (see the argument in Kimmins and Scoullar 1987). The soil leaching simulation will be improved in FORCYTE-12 when an explicit treatment of water is added.

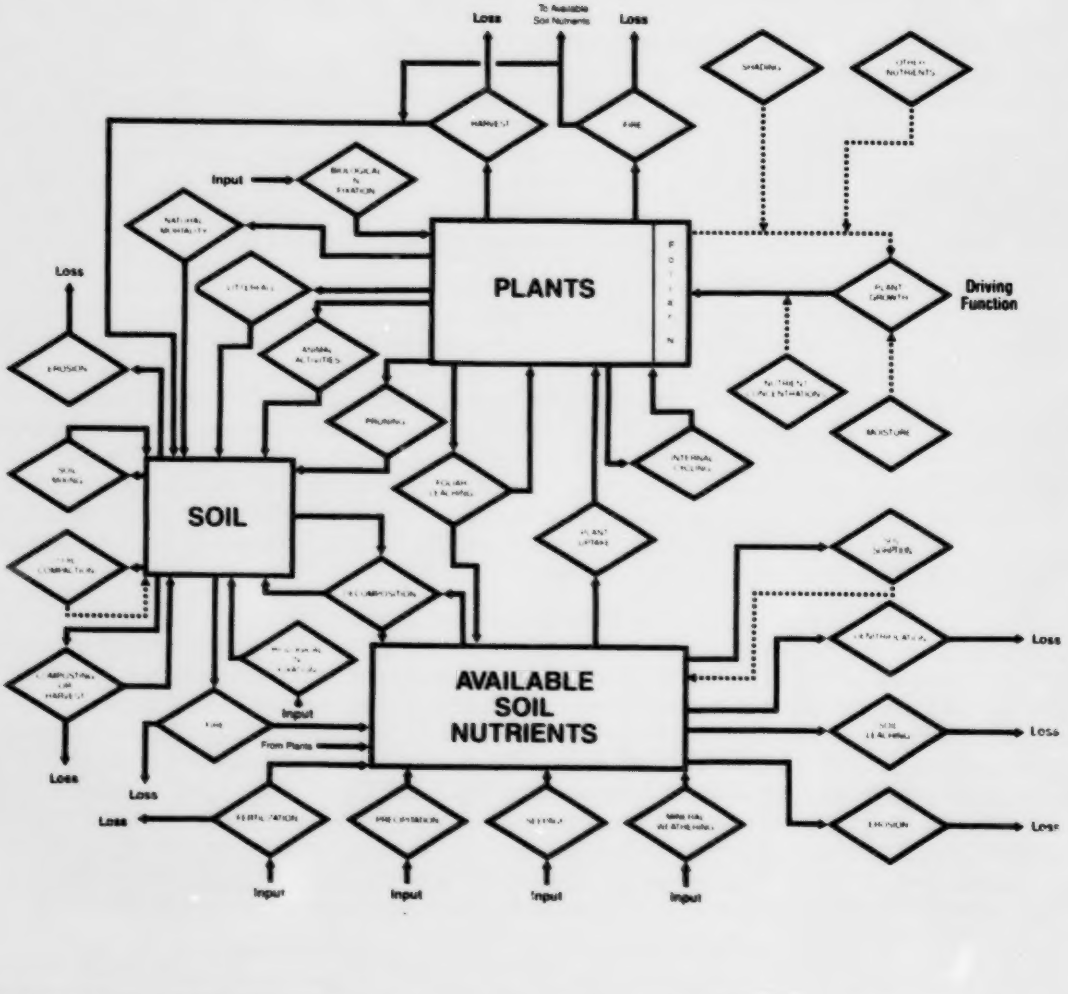
Loss
To Available Soil Nutrients
Loss
SHADING
OTHER NUTRIENTS
HARVEST
FIRE
Input
BIOLOGICAL N FIXATION
NATURAL MORTALITY
PLANTS
FOLIAR N
Loss
LITTERFALL
PLANT GROWTH
Driving Function
EROSION
ANIMAL ACTIVITIES
NUTRIENT CONCENTRATION
PRUNING
MOISTURE
SOIL MIXING
SOIL
FOLIAR LEACHING
INTERNAL CYCLING
PLANT UPTAKE
SOIL COMPACTION
SOIL SORPTION
DECOMPOSITION
DENITRIFICATION
Loss
BIOLOGICAL N FIXATION
COMPOSTING OR HARVEST
AVAILABLE SOIL NUTRIENTS
Input
FIRE
From Plants
SOIL LEACHING
Loss
Loss
Loss
Loss
FERTILIZATION
PRECIPITATION
SEEDING
MINERAL WEATHERING
EROSION
Loss
Input
Input
Input
Input

FIGURE 2. Major compartments and transfer processes represented in FORCYTE-11.

Phosphorus sorption by the mineral soil may be simulated if the user provides input data that define soil sorption/desorption curves. These are used by the model to determine equilibrium quantities of available soil phosphorus, with desorption occurring as this P is taken up by plants. The model actually simulates two P cycles: a plant-forest floor-plant cycle that excludes sorption-desorption processes, and a forest floor-mineral soil-sorption/desorption-plant cycle. These two cycles are linked by simulations of soil mixing, leaching of "available" P, and fire (which mineralizes organically bound P). The user has control over assumptions about the rate and extent of desorption, and the quantity of irreversibly bound P.

Although there is no major horizontal spatial representation in the model at present (this is planned for FORCYTE-12), the model does permit the user to represent spot fertilization, pile-and-burn, or windrowing treatments. The user defines the proportion of the area involved in the "treatment" (the spot, pile, or windrow), and, by difference, the area outside the "treatment" (unfertilized area, or the "window" between piles or windrows). The two areas are simulated separately (for plant growth, decomposition, etc.) until the effects of the treatment have "worn off". The user defines the percentage of the extra biomass and nutrients added to the "treated" area which must be lost from the site or redistributed back to the "untreated" area by litterfall (which is assumed to fall outside of the "treated" area) before the treated areas are recombined, and the spatial "treatment" effect is discontinued.

2.3 Intended Use of FORCYTE-11

If foresters are to be successful in supplying the growing world population with material resources from the forest, the intensity of management must be increased. If this happens, foresters will have to pay increasing attention to forest soils. The long rotations of the past have permitted foresters to rely on natural processes of ecosystem recovery to ameliorate management-induced soil damage. However, as rotations become shorter, and as intermediate harvests and more complete utilization become the norm, the effects of site nutrient depletion, loss of soil organic matter, erosion, and soil compaction on site productivity, yield prediction, and crop production economics will have to be evaluated. Where these effects are deemed unacceptable, management practices will have to be modified.

Models such as FORCYTE-11 are intended as research and management gaming tools with which to examine the yield, yield sustainability, economics and energy efficiency of alternative crop management strategies. For example, such models can be used to evaluate the possible consequences for yield and soil condition (nutrients and organic matter) of short rotations (Fig. 3A,B), or to compare the effects of various combinations of rotation length, utilization level and management intensity on these parameters (Fig. 3C,D). Perhaps the optimum use of the model is to rank the consequences of a wide variety of silvicultural systems, in terms of yield, economy, energy-efficiency and ecosystem condition (Fig. 4). Comparable figures are not yet available for FORCYTE-11, which is in the calibration/evaluation stage. The management parameters and natural events that can be simulated in FORCYTE-11, and the soil processes that can be represented, are listed in Tables 1 and 2. Table 3 summarizes locations and species where FORCYTE-10 has been used and evaluated.

FORCYTE-10 is available in FORTRAN for use on a 512 k or 640 k IBM or IBM-compatible microcomputer. FORCYTE-11 will be available later in 1987 for use on microcomputers equipped with 386 microprocessors (32-bit). Both versions are also available for mainframe use, but the optimum application of these models is in multi-run gaming to explore the consequences of a large number of different possible combinations of silvicultural treatments. Such multi-run gaming becomes too costly on a mainframe, but is "free" after the initial purchase of the microcomputer. Models such as FORCYTE can be used as an educational tool, as a test of the sustainability management strategies formulated according to other criteria, as a test of the validity of conventional HB yield predictions, and as a means of simulating complex, multi-factorial experiments that can never be conducted in real life for lack of space, time and resources. Because such models focus on questions of soil fertility and plant-soil interactions, they have considerable potential for use in soil-related research and management decision-making.

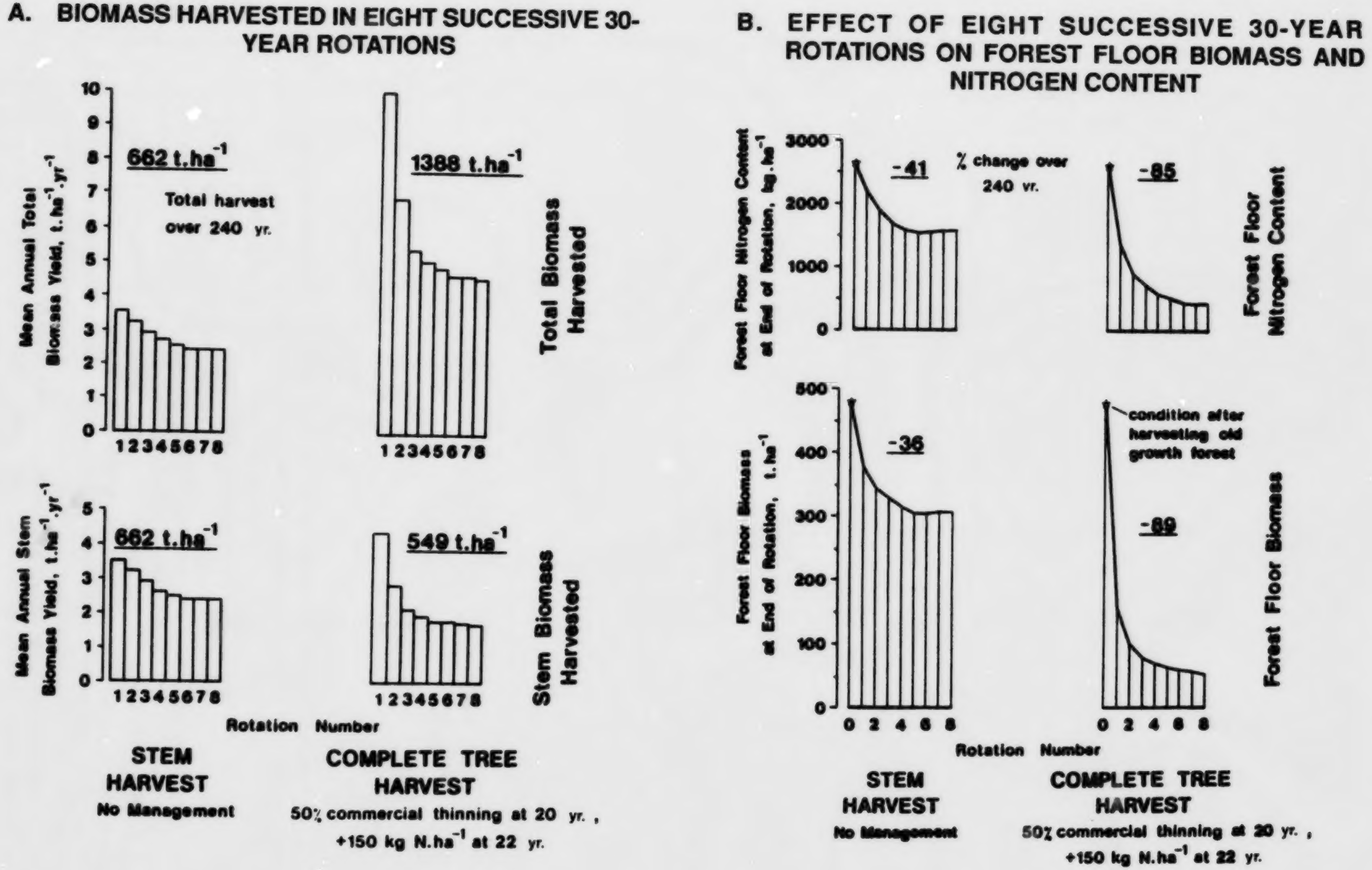

FIGURE 3. Example output from an earlier version of FORCYTE (FORCYTE-10).
A. Predictions of biomass harvested over eight successive 30-year rotations at two levels of management.
B. Predictions of changes in soil organic matter and nitrogen content accompanying the scenarios in A.

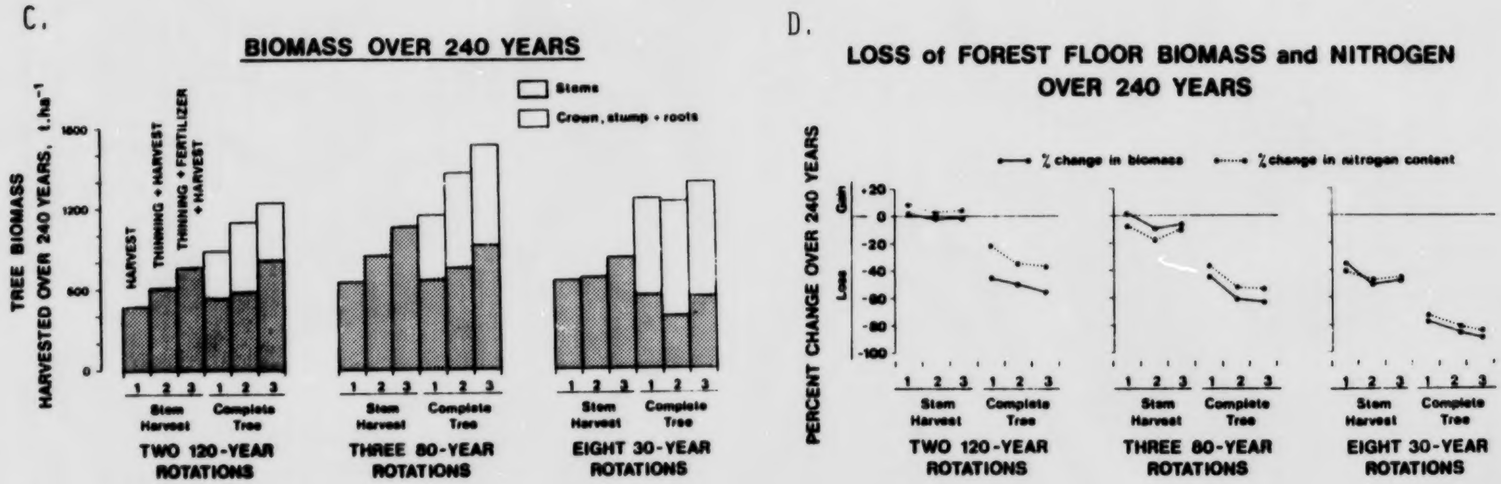

FIGURE 3. C. Predictions of biomass harvested over a 240-year period with three rotation lengths, three levels of management and two levels of utilization.
D. Predictions of changes in soil organic matter and nitrogen content accompanying the scenarios in C.
These figures were produced from runs calibrated for Douglas-fir growing on a medium site in the CWHa subzone on central Vancouver Island.

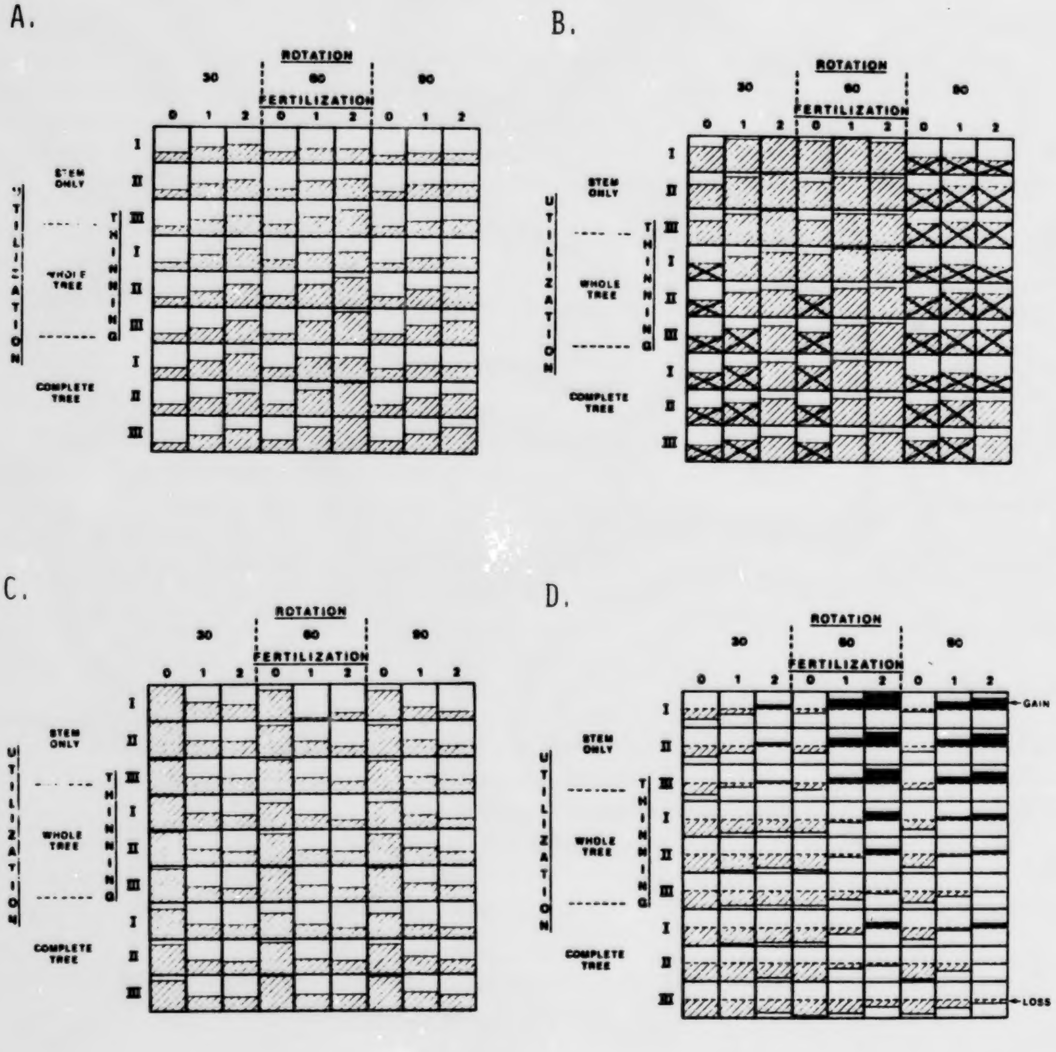

FIGURE 4. Example of output from 81 runs with FORCYTE-10 representing a 3x3x3x3 factorial experiment: three rotation lengths (30, 60, 90 yr), three fertilization levels (none, medium, and heavy), and three utilization levels (stem only, all above-ground biomass [WT], and both above- and below-ground (stump and roots) biomass [CT]). Results for four parameters are given. A = stemwood harvested over 180 years. B = financial benefit/cost ratio. C = energy benefit/cost ratio. D = ecosystem nutrient inventory. For each parameter, the 81 runs were ranked in order of performance for the particular parameter. The cells of the diagrams are shaded in proportion to the parameter value for that cell relative to the maximum parameter value in all 81 runs for that parameter. It can be seen that particular scenarios vary widely in their relative performance according to the parameter being considered. In D, the ecosystem nutrient inventory, the cells are divided into two. Cross-hatching indicates nutrient depletion (the greater the area of cross-hatch, the greater the depletion). The solid black shading indicates site nutrient augmentation. The model was calibrated for the same data set as used in Figure 3 (Douglas-fir, medium site, Vancouver Island).

3 CONCLUDING STATEMENT

All models of biological/ecological systems are to some extent wrong. We can build model aeroplanes that can do everything a real aeroplane can do, so that the model becomes indistinguishable from the reality it represents. We cannot do that with biological/ecological systems. Although we can make a model bird that flies, sings and looks like a real bird, we cannot build a model bird that can lay an egg which hatches into another bird of the same species and can also reproduce itself sexually.

TABLE 1. Management options in FORCYTE-11[a]

Site preparation	- mechanical or fire (ploughing, broadcast burn, windrow, pile-and-burn)
Regeneration	- planting (any size/age of seedling/sapling/ tree); coppice/root suckering, or natural seeding; monocultures or mixtures
Weed competition	- for light or nutrients by herbs, shrubs, or non-crop trees. Control of competition (manual or chemical)
Stand density control	- spacing or pre-commercial thinning; random or other defined spacing strategy
Thinning (commercial)	- high, low, random, or other defined thinning regime
Final harvest	- clearcut harvesting
Utilization level	- any defined proportion of any plant (or soil) component may be harvested at any time
Rotation length	- annual cropping, or short, medium or long (e.g. centuries) rotations
Fertilization	- broadcast or spot; single or multi-nutrients; inorganic or organic
Pruning	- removal of any defined proportion of live and/or dead branches
Herbivory	- e.g., insect defoliation of trees; wildlife browsing on herbs or shrubs
Fire	- prescribed stand or slashburning, or wildfire
Litter raking/slash harvest	- harvest of ectorganic layer, or of logging/thinning slash at any time. Upper soil layer(s) can also be removed

[a] The user decides which of these options are to be simulated, and how. Very simple or very complex scenarios can be simulated.

TABLE 2. Soil processes or management impacts on soil that can be represented in FORCYTE-11[a]

Organic matter decomposition, mineralization, immobilization humus decomposition and mineralization
Soil CEC and AEC, separately for organic matter and mineral soil
Soil sorption/desorption (e.g., of phosphorus)
Soil leaching
Soil mixing (soil animals, or mechanical mixing)
Root distribution by soil layers, according to nutrient availability
Allelopathic effects on decomposition
Organic matter substrate effects and plant effects on the ionic forms of nitrogen
Soil compaction and recovery from it
Soil erosion (sheet erosion, rather than mass wasting)
Denitrification (not presently operational)
Litterfall (and root mortality) inputs of organic matter and nutrients to the soil
Nutrient uptake from the soil and competition for soil nutrients by plants

[a] Because some of these processes are either poorly understood or poorly documented for a particular site, the user may wish to omit any or all of them from the simulation, and can do so. However, the user is reminded that omitting the simulation of a process that is known to be important is as large an assumption as including it, and may lead to as great or even greater error than would occur by including a conservative simulation of the process.

TABLE 3. Locations and species or genera where FORCYTE has been or is being tested or used[a]

British Columbia	- Douglas-fir, lodgepole pine
Alberta	- aspen
Ontario	- black spruce, short rotation hardwood energy crops
New Brunswick	- in conjunction with acid rain research
Newfoundland	- balsam fir
Washington	- Douglas-fir
Oregon	- western hemlock
California	- various coniferous species
N.Carolina	- loblolly pine
Alaska	- white spruce
Finland	- Scots pine
UK	- Sitka spruce
South Africa	- pines
Brazil	- *Eucalyptus*
New Zealand	- radiata pine, *Eucalyptus*
Japan	- *Cryptomeria japonica*
Indonesia	- bamboo talun-kebun agroforestry

[a] The model has been used as a teaching and research tool without recalibration for local species in a variety of other locations (mostly universities).

None of the FORCYTE models can "lay an egg". They are all imperfect representations of forest ecosystems, yield, and soil processes. However, the 8-year development up to FORCYTE-11 has produced a representation of an ecosystem and its management that seems to offer a significant advantage in teaching, research and management gaming over conventional stand yield models, or models of individual plant or soil processes. The model has received considerable interest across North America and elsewhere in the world, and it is hoped that it will assist forest resource managers in British Columbia in the evaluation of their resource management strategies. When one looks at the wide range of adverse soil impacts of forest management in this province, it is hard to avoid the conclusion that foresters need all the help and analytical tools they can get. Any readers interested in learning more about the model or in obtaining a copy should contact the senior author.

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SESSION 2 DEGRADATION/PRODUCTIVITY

SILVICULTURE - A SITE DEGRADATION CONSIDERATION?

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ABSTRACT

The effects of forest harvesting and site preparation practices on site productivity have been recognized in British Columbia and action is being taken to reduce site degradation. However, the broader role of silviculture in relation to site degradation has not been generally recognized. This paper explores the site degradation implications of the choice of silvicultural system, species selection, site preparation, stand tending, and the intensity of silvicultural practices.

1 INTRODUCTION

Degradation of forest sites has become a recognized resource management issue in the province of British Columbia. To date the focus of concern has been on various aspects of forest harvesting and site preparation. These activities have a direct and general immediate influence on forest site productivity. However, forest management involves other activities that can have both direct and indirect influences on sites, particularly with long-term implications for site productivity. In this paper I address how silvicultural strategies for stand establishment, species mixes, stocking levels, and stand treatments can have profound influences on site productivity.

It is not the intent of this paper to inflame silviculturists; rather it is to support their important role in establishing and maintaining healthy forests. Without recognition of this role and support for it, the gap between what is done and what should be done widens, at the expense of forest site productivity. In short, the aim of the paper is to initiate discussion and perhaps broaden the scope of research on degradation of forest land.

2 SITE DEGRADATION - AN EXPANDED DEFINITION

The term degradation is generally defined, in relation to soil, as any significant reduction in the fertility of a soil, whether in the course of its natural development or by direct or indirect human action. It usually is applied to effects of erosion, compaction, reduced infiltration, and nutrient loss. It is also defined as the changing of a soil to a more highly leached and more highly weathered condition, generally accompanied by morphological changes (e.g., development of an Ae horizon) (Ford-Robertson 1971).

The Silviculture Policy of British Columbia defines degradation as "the reduction of productivity resulting from soil damage due to unacceptable logging disturbance."[1]

I would like to maintain the aspects of soil damage, but expand the definition to include such aspects as microclimatic and hydrologic relations, and vegetation — factors that affect site productivity and can be altered by silvicultural practices.

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[1] B.C. Ministry of Forests, Policy Manual, Silv. Chapter, Section 009, p. 11, 1984-05-24.

Further, I would like to include in the definition of site degradation the aspect of value — the value to our society. If after harvesting, a site is not producing products of value for our society, then it should be considered to be in a degraded condition. For example, consider that a decision is made to improve site productivity with a rotation of deciduous cover after harvesting the old growth. This can be accomplished through managing a commercial deciduous forest (goods are produced) or the area can go to brush (goods are not produced for society, unless the area is utilized by wildlife). Thus, it is possible that a large proportion of the "not satisfactorily stocked" (NSR) area in British Columbia is, by definition, degraded (it is difficult to conceive that the full extent of NSR-brush fields in British Columbia can be considered as suitable wildlife habitat).

Value has greater meaning than just the presence of commercially valuable species. If a site has the potential to produce high quality peeler logs, but through lack of stand tending is producing pulp quality logs, there has been a loss in value, and a degradation of site value. In order to determine this aspect of site degradation, it is necessary to have clearly established management objectives for five forest units. To date this has not been done except in general terms in the province.

If the net result of a stand treatment or prescription is to predispose the forest crop to insect or disease problems, that treatment should be considered as site degrading. For example, if a site is infected with *Phellinus weirii* and Douglas-fir is planted, there is a high probability that the crop will not reach rotation age without severe losses. Thus, since the site is not producing a useful product for our society, at or near the capability of the site, the site has been degraded.

Some foresters would contend that lost value does not constitute degradation. If the value lost is not significant and the time frame over which the problem has either developed or will become rectified is only a fraction of the rotation (e.g., 10%), I would agree. However, if the value lost is significant, the time frame is long (e.g., greater than 15% of the rotation), and the cost of rehabilitation is high, the site may very well be written off by management staff. In this case the site should be classified as degraded.

3 AN OVERVIEW OF SOME FORESTRY ASPECTS IN BRITISH COLUMBIA

Forest management in British Columbia is primarily at the exploitation stage. The vast natural forest reserve has formed the basis of the province's wealth. Over the past few decades there has been a recognition that harvested areas must be restocked and that stands should tended. This recognition has gained popular support in recent years and a considerable amount of money is being channeled into forest management.

The ecological classification of the forest land base has been a significant accomplishment and provides a basis for sound forest management decisions. It is most unlikely that serious off-site plantings, such as those experienced in Saxony (Lutz and Chandler 1946), will occur in the province.

However, balancing these two positive developments are several potentially serious factors. First, annual allowable cuts (AAC's) are essentially fully committed in the province. Thus, while we are pioneering in forest management and silviculture, there is limited room for error and little time to experiment with treatments. Most other countries accumulated a body of knowledge prior to fully committing the forest resource to capital-intensive processing industries. Are we, in British Columbia, to benefit from the substantial body of world silvicultural knowledge, or will we repeat the same mistakes (at a more critical time in the evolution of our forest industry)? Second, the silviculture and management staff of forest units is continually changing in British Columbia, particularly at the field level. Continuity of experience is essential for a sound body of silvicultural knowledge to be gained. Third, while the forests of British Columbia, are managed within an ecological classification framework, much has still to be learned about the functioning within the numerous ecosystems. For example, little is done at the field level to maintain populations of insectivorous birds in managed stands (e.g., establishment of nesting habitat). In German forests this aspect of ecological management has been in place for a considerable period of time. While forests can be managed without due consideration to the natural ecosystem, such management will require inputs to maintain the balance of nature. In the case of a lack of insectivorous birds, insecticides or special treatments may be necessary to keep insect populations at endemic levels. Fourth, management units are large and staffing levels are small, with the result that forest management is extensive rather than intensive. With extensive management it is possible that small problems are not seen or acted upon quickly, with the result that they can become quite significant before action is taken (e.g., the current extent of NSR).

4 SILVICULTURAL PRACTICES

Five aspects of silviculture will be discussed in this section: silvicultural systems, species selection, site preparation, stand tending, and the intensity of silvicultural practices.

4.1 Silvicultural System

A silvicultural system is defined as the process by which the crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of woods of a distinctive form (Troup 1952). Silvicultural systems have evolved over the centuries and range from the Clearcutting System to the Selection System. The choice of a system for a particular area is based on silvicultural and economic factors. Troup notes that these factors are sometimes antagonistic to each other, so that although a system may be entirely suitable from the silvicultural point of view, it may be inapplicable owing to its economic disadvantages, and vice versa. An interesting point is that the economic factors, particularly the costs of logging a natural stand, are apparent from the outset, while silvicultural factors can take many years to become apparent. To be successful over a long period of time, a silvicultural system must be both economically and ecologically sound.

Given the ecological diversity and the number of commercial tree species in British Columbia, one would expect to find the full range of silvicultural systems in use. However, with the exception of the Interior Douglas-Fir Zone and the Ponderosa Pine-Bunchgrass Zone where selection, shelterwood, and seed tree systems are used, the clearcut system is essentially ubiquitous. The clearcut system is by far the easiest system to apply, and produces the lowest cost wood (this is a short-term benefit if the system is not suited to the site and species). The clearcut system is not recommended for unstable slopes or brush-prone sites (Troup 1952). A system can be applied even where it is not suited, but the long-term rehabilitation costs will most likely exceed the initial savings in not using a more appropriate system. Will this be the case in British Columbia? Schwab has presented information at this workshop on the site degradation due to mass wasting. The need for a special, major program (i.e., the Forest Resource Development Agreement) to correct significant reforestation problems may indicate that there are shortcomings with the wholesale adoption of the clearcut system. Will the practice of creating large or continuous clearcuts increase insect damage in plantations (Stiell and Berry 1985)?

Silviculturists in British Columbia have a large selection of systems that can be used to reproduce and maintain the flow of forest products (see, for example, Burns 1983). There is evidence of site degradation resulting from the widespread application of the clearcut system, yet the bulk of the research and management effort is directed to correcting the symptoms and not the underlying cause.

4.2 Species Selection

Species selection must be based on the ecological requirements of the species (Klinka and Feller 1984). This is done operationally in British Columbia, and off-site planting is generally a thing of the past. One additional factor that is important for successful tree growth on some sites is an understanding of successional pathways. The fact that some pathways include one species or community of species that improves a site for subsequent crops has only been partially explored by silviculturists. Results from work done with short rotations of red alder, followed by Douglas-fir, indicate that the topic should be more fully explored (Tarrant and Trappe 1971).

Consideration of successional pathways leads to a basic questioning of the term "rotation." Foresters refer to rotation as a changing of age classes of a commercial tree species on a site, while agriculturalists refer to a rotation as the changing of commercial species, with a view to improving or maintaining site productivity. To what extent should foresters consider practicing an agricultural rotation, and on what sites? Given the objectives of site preparation and stand tending in British Columbia, is it possible that we are forcing some sites to skip important successional stages? Will this lead to site degradation?

Foresters have been concerned for centuries about the potential for site degradation as a result of successive conifer crops on the same site (Lutz and Chandler 1946). This concern led Bublinec (1980) to undertake detailed research in second and third rotation pine and spruce plantations in Czechoslovakia. He found that sites were changed by high mass conifer monocultures, but the changes were not of a negative manner, except on poor sites where fertilizers were recommended to maintain site productivity. Does the same hold true for British Columbia, given our ecosystems and silvicultural practices?

4.3 Site Preparation: Brush Control

The aspect of site preparation that is discussed here is brush control for establishment of conifer seedlings. The concern is two-fold: first, for the short-circuiting of important successional pathways; and second for the survival of the seedlings themselves.

At a recent vegetation management workshop, a clear correlation was made between seedling growth and brush competition: the lower the competition, the better the growth (Wagner 1986). In fact, attempts to totally control the brush produced the best initial growth. What are the long-term implications of brush control? Is it possible that radical measures to promote establishment and rapid initial growth will in fact lead to site degradation and lower stand volumes at rotation age (McNabb and Campbell 1985)?

Aside from their nutrient contributions, brush species can also provide other beneficial influences on seedlings. Sutton (1984) reported that spruce seedling mortality due to frost increased when brush species were removed with herbicides. Removal of competing vegetation increased the incidence of fusiform rust in slash pine plantations (Burton *et al.* 1985). Some unwanted "weeds" develop into nurse crops, providing important climatic amelioration for conifers (e.g., aspen and Engelmann spruce) (Shepperd and Jones 1985). While it is clear that brush species compete with conifer seedlings on many sites, it is critical to know the extent to which brush management influences site productivity and at what level of intensity the influence becomes negative and degrades site productivity.

4.4 Stand Tending

The aspects of stand tending to which I will refer are fertilization and thinning. These treatments generally produce positive results; however, given certain conditions, the overall effect on a stand can be negative. For example, Schnekenburger *et al.* (1985) reported an increase in the extent of snow damage in jack pine following fertilization. The initial effect of thinning is to increase stand susceptibility to snow damage (Godman and Olmstead 1962; Williams 1966). Bella (1985) reported a significantly higher incidence of gall rust, leader weevil damage, and needle cast infection in thinned versus unthinned stands of lodgepole pine. Harrington *et al.* (1985) reported an increase in black stain root disease following thinning of Douglas-fir. Small mammals can cause serious damage to thinned stands of lodgepole pine and, when a stand is fertilized, the impact is of even greater magnitude (Brockley and Elmes 1985; Sullivan 1985). To what extent do thinning and fertilizing present a site degradation hazard in British Columbia?

The degree of canopy closure is inversely related to the amount of understory vegetation. The goal of silviculturists in British Columbia is to maintain full site occupancy and achieve canopy closure as quickly as possible. This leads to a reduction of understory vegetation. Is this appropriate for all sites? Youngberg (1966) presented information to suggest that understory vegetation provides a range of silvicultural benefits to a site, including improvements in nutrient cycling and humus form development, influences on microbiological processes and suppression of soil-borne pathogens. Youngberg concluded that a more thorough understanding is needed of the role of understory vegetation, and until this is achieved, foresters will be treading on thin ice in many of their stand manipulations.

Efforts to control the mountain pine bark beetle have resulted in extensive clearcuts. If the areas are reforested with pine, the same epidemics may redevelop within the present rotation. One way to avoid such a development is to tend the stands in such a manner that the expanse of essentially one age class is broken up. This can be achieved by focusing efforts that will allow an early harvest (patch cutting) on good sites, creating a mosaic of age and size classes that reduces the acreage highly susceptible to beetles at any one time (Amman and Safranyik 1985). Will such measures be taken or will present control measures lead to a repeat of the epidemic problems? This is a site degradation concern.

One of the implications of this discussion is that, given certain conditions, it is better to have several stand tending treatments over time rather than only one. Considering that it is the intent of silviculturists in British Columbia to limit the number of entries into a stand, it is important to define the critical conditions that require multiple entries in order not to expose a stand to potential degradation.

4.5 Intensity of Silvicultural Practices

As previously noted, forest management in British Columbia is extensive rather than intensive because of large management units and small staffing levels. In effect, the forests are, by and large, left to Nature with minimal interference. Given this situation, it is prudent to provide as many "tools" as possible to allow Nature to do its role. An example would be to provide habitat for beneficial organisms such as insectivorous birds (Dickson *et al.* 1979) and ants (Goesswald 1971). Is this being done in British Columbia, or are we working against such a harmony? I suggest that our knowledge of forest ecosystem function is far from complete and that the net results of our silvicultural practices are harmonious only by accident. I believe there are grounds for us to be concerned about site degradation.

5 CONCLUSIONS

Silviculture is necessary in the management of forests. It is perhaps more than necessary: it is critical for our forest-based economy, our wildlife, our water, and other forest-dependent resources. Practiced with a sound ecological understanding, silviculture can be effective. However, without such an understanding, the net result can be a serious degradation of sites, and of all the products our society gains from forested lands. I believe that the implications are far more serious and potentially widespread in British Columbia than the presently recognized point-source factors that cause site degradation.

I believe that we would do well to consider expanding our definition of site degradation to include silvicultural impacts, and to focus our attention on avoiding a "future shock".

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SESSION 3

Predicting/Controlling Forest Soil Degradation

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SESSION 3 PREDICTION/CONTROL

APPROACHES TO PREDICTING SOIL DEGRADATION[1]

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ABSTRACT

The most critical decision to be made when predicting soil degradation is the choice of an appropriate predictive model. This paper discusses a number of questions which need to be answered before a logical choice of model can be made. The presentation also discusses some characteristics of predictive models and how these characteristics should influence the use of a model. The applicability of an existing model (the Universal Soil Loss Equation) is discussed with reference to its suitability for specific interpretive questions. Finally, some interpretive approaches, which are reasonable within the limits of current understandings, will be suggested and some questions which need to be answered when assessing predictions of potential degradation will be asked.

1 INTRODUCTION

The prediction of soil degradation is a complicated problem. Dramatic examples of soil degradation, such as landslides, massive gully erosion, and exposed bedrock caused by sheet and rill erosion, are easily recognized but less easily predicted. The problem of prediction increases as the required precision and accuracy increase. As will be apparent from the other papers presented at this workshop, the quantification and prediction of forest soil degradation has received little attention in British Columbia. There will be no easy answers presented in this paper. The basic research into the processes, magnitude, and costs of soil degradation, which is necessary to provide unambiguous answers, has simply not been done in British Columbia, nor the necessary development and testing of predictive models. The predictions we do make will be based on many untested assumptions. If we are to use these predictions wisely, we must understand the basis for these assumptions, how realistic they are, and how possible errors in the assumptions are likely to affect our predictions.

The following example may serve to show that significant problems have yet to be resolved. Soil degradation has been identified as a major concern in the Canadian agricultural sector (Standing Senate Committee on Agriculture, Fisheries, and Forestry 1984; Anderson and Knapik 1985). Recent reports by Sprout (1984) and Fox and Coote (1986) have estimated significant "farm gate" losses related to soil degradation. However, the estimates of economic loss given in Sprout (1984) and Fox and Coote (1986) are in substantial disagreement, both in the magnitude of losses and in the relative importance attached to the different types of degradation. Sprout estimated the total cost of erosion and compaction in the South Coast Mainland region to be approximately $15.1 million, of which $12.5 million is attributed to soil compaction, $0.4 million to water erosion, and $2.2 million to wind erosion. Fox and Coote, including Vancouver Island in their study, estimated total costs to be about the same, but a $7.5-12.5 million loss for water erosion (as opposed to $0.4 million) and less than $0.1 million for wind erosion. These differences result from the different models used to estimate the degree of degradation and the economic costs associated with it.

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[1] L.R.R.C. Contribution No. 86-15.

The discussion of discrepancies in cost estimates for agricultural soil degradation is a caution to us when discussing soil degradation in forestry because, while we think we understand much of the soil degradation problem in agriculture, we have a much poorer understanding of the problem in forestry. The source of the discrepancies can be found in the models used, and so the choice of models is a major theme of this paper.

2 BASIC QUESTIONS

2.1 What Constitutes Degradation?

Before beginning the discussion it seems appropriate to define soil degradation. Soil degradation is a change in the physical or chemical properties of a soil, brought about by management or lack of management, which reduces the ability of a soil to support some desired used. Perhaps the definition should be modified to include only those changes requiring more than normal management effort to correct. For example, the loss of soil fertility through cropping, if it is depleted to the point where it becomes economically unfeasible or marginal to correct, should be considered to fit this definition.

2.2 How Is Degradation to be Measured?

2.2.1 What to measure?

Measurements of soil degradation currently use units of mass/volume for compaction, or mass/unit area for erosion. However, these values are of limited utility to a resource manager attempting to allocate limited financial resources to the solution of a number of problems. While measurements of change in soil properties are a necessary first step, these values must be translated into terms that the resource managers can understand and base decisions on. For example, soil compaction is detrimental to plant growth when it reduces the aeration of water retention capacity of a soil to below a required level, but may be beneficial in coarse textured soils if it increases the water retention capacity of the soil.

Ultimately, the manager would like to attach economic units to the measure of degradation. To do this requires three steps: 1) the quantification of change; 2) quantification of the production, performance loss or off-site impact associated with different levels of change; and 3) the assignment of economic values to performance loss or off-site impacts.

Another important measure that has received little attention is the natural rate of recovery. This is much more important in forestry than it is in agriculture because of the much longer crop rotations in forestry. Estimates of production losses or economic costs that ignore natural recovery rates will overestimate the related costs and, alternatively, estimates of production losses that erroneously assume short-term recovery periods will underestimate the related costs.

Finally, the manager should know the effectiveness and the costs of alternative practices that may be used to minimize management impacts or to ameliorate existing degradation.

2.2.2 How do we measure degradation?

The actual process of measuring soil degradation presents problems, even if we restrict ourselves to the simpler task of quantifying physical or chemical changes. For example, bulk density measurements are difficult in soils with high coarse fragment contents; high spatial variability requires large core sizes to encompass microvariation; and, for many soils, the problem of compaction is confined to a thin soil layer, which may be difficult to sample adequately. The measurement of soil erosion is no easier. Current methods require either some form of catchment to collect the eroded material or the monitoring of micro-changes in soil elevation to quantify actual losses.

2.2.3 How do we estimate degradation over areas?

Soil degradation is an area-related, not a point-related, problem. Techniques developed to measure point-specific degradation fail to address the problem of changes over area. Estimates of areal impacts are based on the extrapolation of point-specific data. This extrapolation requires the use of techniques of inference, preferably statistical inference. In most cases, large spatial variability requires that large numbers of samples be taken to demonstrate statistically significant changes in soil properties unless the changes are dramatic. The temptation to accept as important those changes which cannot be demonstrated statistically should be resisted. Perhaps the standard 95% significance level used in much routine plot work is too rigorous, but a significance level of only 80% implies a 1 in 5 chance of the conclusion being wrong.

2.3 How Is Degradation to be Predicted?

So far, I have discussed only the problem of measuring or estimating existing degradation. It should be pointed out that the current national and provincial concern over soil degradation is based not on measured soil degradation but on the results of predictive models or expert opinion (Sprout 1984; Anderson and Knapik 1985; Fox and Coote 1986). The models have had little or no validation in British Columbia; they have been applied outside the conditions for which they were developed, and they have been applied to soil and terrain inventories which do not provide all of the data necessary to use the model. (The only erosion data which could be used to test the Universal Soil Loss Equation are limited sets from the Peace River region and a very limited set from the lower Fraser Valley. There are not, to my knowledge, any data against which the estimates of compaction were tested nor are there any data for British Columbia relating yield reductions to soil erosion or compaction). Clearly, to evaluate the applicability of these models and the validity of the results, we must understand the models being used.

The prediction of soil degradation is analogous to the problem of measuring existing degradation in that the prediction must be based on estimates of soil properties extrapolated over area. The problem is compounded by the need to interpret the expected response of soils with different combinations of properties. There are three basic types of models used to predict soil responses: 1) theoretical models, 2) empirical models, and 3) expert system models. The differences between these models can be explained rather simply with the following example.

Assume you wish to know how long it will take an object (e.g., a golf ball) to fall from a given height to the floor without actually having to drop it. The theoretical approach would use calculus to derive an equation that relates the distance above the floor and the acceleration due to gravity to the time required for the object to fall, and then it would solve the equation. The empirical approach would use a stop watch to measure the time required for a golf ball to fall to the floor from different heights, derive a predictive equation to predict time of fall from distance of fall, and then apply the equation to the data for the question asked. The expert systems approach would develop a set of conditional rules to predict the falling time of golf balls. The rules would reflect the thought processes used by a number of people who have extensive experience with falling golf balls (perhaps golfers), but who do not understand the physics of falling bodies or have access to rigorous empirical models of falling bodies.

3 MODELS

As with nearly all classifications, the distinctions between the three types of models outlined above are not always clear, but the concepts offer a basis for discussion. An understanding of the underlying principles and limitations of the models used to predict soil degradation is essential to their wise application. In the following discussion I will use examples not directly related to forest soil degradation, but which utilize well-understood and documented principles.

3.1 Theoretical Models

Theoretical models are based on an understanding of the physical and chemical mechanisms governing soil responses to treatment. If the model is correct, it can be used to predict response under any conditions so long as the necessary inputs are known. Using a simple analogy, to predict the solid volume of individual hollow cylinders, the theoretical approach would use geometric relationships to formulate the equation:

$$\text{Solid Volume} = (r1^2 - r2^2)h\pi \qquad [1]$$

where $r1$ = outside radius
$r2$ = inside radius
h = height of cylinder
π = 3.14

3.2 Empirical Models

Empirical models are based on observed responses to treatment without concern for the mechanisms governing the response. In their crudest forms, the predictions of response are based on observation without recourse to scientific or statistical rigor. As such, they are the basis for much intestinal inference or professional judgment. In their more sophisticated forms, the predictions of response are based on rigorous statistical observation and are restricted to the range of conditions for which the models were developed. In these cases, they can be an effective interpretive tool. Continuing the analogy of predicting the solid volume of hollow cylinders, the empirical approach would:

1) take a sample of cylinders (for this example, the dimensions of the outside radius, the inside radius, and the height for 10 cylinders were drawn from a random number table);

2) measure solid volume (the dependent variable) by liquid displacement, (for this example the solid volume was calculated using equation [1]);

3) measure a number of properties which are thought to be important to the prediction of solid volume. (For this example, wall thickness, the outside diagonal [length of the diagonal from the top at the outside of the cylinder to the bottom at the outside of the cylinder], the inside diagonal, the difference between the diagonals, the angle forced between the base of the cylinder and the outside diagonal, and the outside circumference were all calculated in addition to the cylinder height, inside radius, and outside radius. Technically, only one of the radii and one of the diagonals should be used together because they are related.)

4) run a multiple, stepwise regression analysis, using volume as the dependent variable and the measured properties as the independent variables, to define a predictive equation in terms of the most useful of the properties measured.

The stepwise regression analysis selected height, angle of the outside diagonal, thickness, and inside diagonal to form the equation:

$$\text{Solid Volume} = 200h - 34a + 128t - 22d2 \qquad [2]$$

where h = height
a = angle of the outside diagonal
t = wall thickness
$d2$ = diagonal 2

R^2 (adjusted for the small sample size) = 0.978

The R^2 value of 0.978 indicates a good fit of the predictive equation to the data, even accounting for the small sample size. This point will be discussed later.

3.3 Expert Systems Models

Expert systems models are a form of empirical model in which the decision processes used by experts to make interpretations are codified as a set of rules which can be used to make the same interpretations as the experts who worked on the model. They are used to answer equations for which there are no theoretical or statistically based empirical models. In the example of the hollow cylinders, a group of experts would be requested to outline their methods of estimating the solid volume of hollow cylinders, and a program would be written to duplicate the logic used. The resulting model would be tested and the logic modified to conform to empirical tests. In practice, the procedure may utilize empirical and theoretical models, where available, and augment them with codified expert opinion. To the extent that the expert opinion is well founded and that the problem addressed is not outside the experience of the experts, or that it reflects real relationships, the model can be effective.

3.4 Limitations

There are, of course, dangers involved in the application of any of these models. The theoretical model, if it represents all of the factors influencing the interpretation, will consistently produce reliable results. The chief danger lies in not fully understanding the problem. For example, Newton's Universal Law of Gravitation was used to predict the presence of Uranus' moons, just recently confirmed by the fly-past of Voyager. We can use the same law to determine the gravitational constant for a baseball at a given distance from the earth, calculate the acceleration due to gravity (Galileo did it empirically), and quite reliably calculate the time it would take the baseball to fall from a height of 2 m to the floor (about 2/3 of a second). If we use the resulting equation to predict the rate of fall of a piece of paper, where wind resistance becomes significant, it fails. There are other mechanisms acting on the process which the universal law of gravitational attraction does not address.

The empirical approach must also be used cautiously. Taking the example of the hollow cylinders, a second set of randomly determined cylinders was produced, the same measurements calculated, and another stepwise regression run (after Wallis 1965).

The resulting equation was:

$$\text{Solid Volume} = -316h + 17d1 + 31a + 9dd \qquad [3]$$

where h = height
d1 = diagonal 1
a = angle
dd = difference of the diagonals

R^2 (corrected for small sample size) = 0.997

It is important to note that, for the two variables chosen as predictors in both equations (height and angle), not only do the coefficients differ, but the signs change. In other words, in equation [2] height is positively related to volume, but in equation [3] height is negatively related to volume. This emphasizes that relationships derived through multivariate analysis should not be considered causal.

The number of samples and properties used in the two regression models was deliberately chosen to demonstrate another potential problem with regression analysis. The probability of obtaining a significant R^2 value is high when large numbers of properties are used with small sample sizes (even if the R^2 is adjusted for small sample size). The probability of the resulting equation being applicable to data other than that used in defining the equation is correspondingly low. Predictive equations based on small sample sizes and/or large numbers of independent variables are generally unreliable.

To demonstrate the dangers of using empirical relationships beyond the limits for which they were defined, or of accepting the relationship as real without an independent validation, Table 1 presents the results of applying the equations [2] and [3] to the first set of hypothetical cylinders. It is important to note that despite the high R^2 values, the error on individual cylinders can be quite high when equation [2] is used to predict the volume of the cylinders on which the equations was based. When equation [3] is used on the same cylinders (cylinders not used in defining equation [3]), the results are illogical. The preceding examples were used to encourage caution in the use of, rather than rejection of, empirical models. Effective empirical models require statistically rigorous sampling designs and generally large sample sizes, and their application should be restricted to the conditions for which they were developed. The Universal Soil Loss Equation, discussed later in this paper, represents an empirical approach that has worked well when appropriately applied.

A significant advantage of the empirical approach is that, when validated and used appropriately, it gives us an objective measure of reliability or confidence. We can estimate probable errors for the population as a whole and estimate maximum probable errors for individual interpretations. For the reader to do so, the R^2 and the standard error of estimate for the regression equation must be given. If conducted with statistical rigor it also removes much observer bias.

The limitations of expert systems models are not so easily demonstrated because these models are developed in response to a lack of adequate theoretical or empirical models. They are subject to many of the same limitations as the other models, but offer the advantage over purely empirical models of making logical sense to the experts who develop them. The inverse relationship between cylinder height and solid volume in equation [3] would have been rejected in an expert systems model. To use the example of falling objects again, an expert system model could be modified to recognize that a balloon has a mass to volume ratio which would make it susceptible to wind resistance and air currents, in much the same way the piece of paper was. However, because it would be susceptible to wind resistance regardless of orientation, it would fall more slowly than the paper.

Expert systems models are as good as the contributing experts' understanding of the systems in question. They have been used with success in the area of medicine (Kunz *et al.* 1978; Szolovits 1980), land management (Pereira *et al.* 1982), and mineral exploration (Gaschnig 1982). Expert systems models offer advantages in that they produce consistent interpretations which can then be tested empirically, they are easily updated in response to new information, and they can be applied by non-experts in a consistent manner. To the extent that expert systems models are validated through rigorous empirical techniques and confined to the conditions for which they were developed, we should have confidence in them; to the extent that they were not validated or confined to the conditions for which they were developed, we should be skeptical.

TABLE 1. Solid volume (cm^3) predicted by equation [2] (derived from the first data set), and equation [3] (derived from the second data set) when applied to the first set of theoretical hollow cylinders

Cylinder	**Real Volume (Equation 1)**	**Equation 2**	**Equation 3**
1	565	554	-1421
2	502	410	- 745
3	518	518	- 666
4	612	557	- 704
5	527	576	- 874
6	427	533	-1435
7	301	226	- 306
8	461	431	- 882
9	122	224	- 126
10	1130	1120	- 873

4 A CURRENT MODEL: THE UNIVERSAL SOIL LOSS EQUATION

The Universal Soil Loss Equation (USLE) is one of the most widely used predictive models for soil degradation (Wischmeier and Smith 1978). It has limited application to forest soil degradation, but is used here because (1) it represents the only popular empirical model addressing a forest soil degradation problem, (2) it has been used extensively in estimating the impact of forestry operations on water quality, and (3) and it provides a handy example. Soil loss (A) is calculated by the equation:

$A = RKLSCP$

where R = a rainfall and runoff factor
K = a soil erodibility factor
L = a slope length factor
S = a slope steepness factor
C = a cover and management factor
and P = a support practice factor.

The model is a hybrid of the theoretical and empirical approaches because the variables chosen for use in the model are based on an understanding of the physical processes that influence particle detachment and transport. Ultimately, it is empirical because the mathematical relationships used to define the factors are derived by regression analysis. The authors of the USLE recognized the empirical nature of their model and they caution users against extrapolating the data beyond the range of properties on which the relationships are based. Some examples of applications of the USLE will be given to highlight how current models can be most appropriately used in our forested systems.

If we can accept that the model reflects the behavior of most soils, we can use it to conduct a sensitivity analysis for soil inventory. That is, we can use it to define those soil variables that will most strongly influence soil erosion and determine the probable error of estimated erosion associated with errors in identifying the relative properties.

To demonstrate the application, the predicted erosion rate of an arbitrary soil will be used as a base for comparison as individual properties are allowed to change. Erosion rates will be predicted as each property varies across a range of conditions. The soil has the following properties:

Property	Base	Range Compared
Silt + very fine sand	35%	(7-64%)
Clay	10%	(1-20%)
Slope	10%	(1-18%)
Slope length	152 m	(15-300 m)
Organic matter	2%	(0-4%)
Duff cover	50%	(5-95%)
Structure	very weak fine granular	
Perviousness	moderate	
R value	150	
Treatment	recently burned	

Figure 1 portrays an application of the USLE to predict the influence that changes in specific soil properties have on soil erosion. The x-axis represents the expected range of any given property in the area being studied. For example, if clay is expected to range from 1 to 20%, then "lowest" on the x-axis represents 1% clay content and "highest" represents 20% clay content. The horizontal line represents predicted erosion for the standard soil (just under 24.64 tonnes/ha). As the value for an individual property increases or decreases relative to the standard soil, the predicted erosion either increases or decreases. The slope of the curve is a measure of the sensitivity of erosion to changes in the property.

It is clear from the graphs that the proportion of the ground covered by duff (forest floor) material has the strongest influence on expected erosion losses. The shape of the curve also tells us that small changes in duff cover at lower cover values are far more important than they are at the higher cover values. Failure to consider duff cover, or errors in determining duff cover (especially at the lower cover values), will lead to serious errors in the estimate of erosion. Under the conditions outlined above, a 5% duff cover results in a predicted loss of 76.16 tonnes/ha, while a 95% cover reduces this to 4.48 tonnes/ha.

The next most important variable is percent slope, followed by the silt + very fine sand particle size fraction and, of less importance, slope length. Soil erosion is relatively insensitive to organic matter and clay content (clay content showed a nearly identical pattern to organic matter content), although cumulatively they could have an impact comparable to slope length. Thus, if we are attempting to predict soil erosion in the study area, soil cover, slope, texture, and slope length are the most important soil variables and we should concentrate our efforts on collecting reliable data for these properties. It should also be pointed out that, without these variables, our estimates may be meaningless.

Models such as the USLE are often used to extrapolate results to conditions for which we have little or no information, as well as to determine factor interaction. For example, the model may be used to determine how degradation caused by a change in one property may be ameliorated or aggravated by a change in another property. I have already discussed the fact that empirical models are not mathematical expressions of process, but only mathematical expressions of correlations; and that correlations do not demonstrate causality. To the extent that these correlations are real, an empirical model such as the USLE may demonstrate some useful interactions. The same caution should be applied when we use empirical models to extrapolate to conditions for which we have little or no experience. It has become common, for example, to extrapolate the USLE to slopes steeper than the 18% on which the model was based. The example below demonstrates an application of the USLE for extrapolating and determining factor interaction.

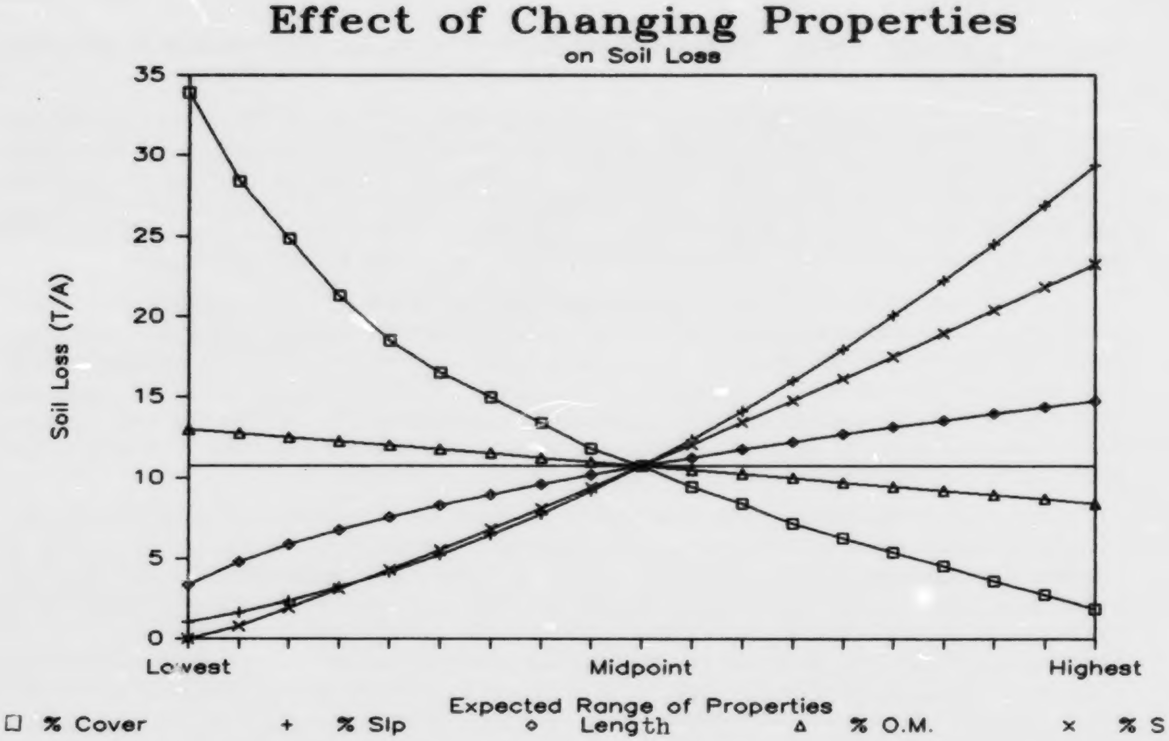

FIGURE 1. Effect of changing soil properties on soil loss.

Figure 2 represents the influence of slope on soil erosion for soil having the following properties:

Property	Value
Sand	35%
Clay	10%
Slope length	30 m
Organic matter	0%, 0-7%, 0-16%
Duff cover	0%
Structure	very weak fine granular
Perviousness	moderate
R value	150
Treatment	recently burned

The top line indicates the predicted soil loss with increasing slope for a 0% organic matter content (O.M.). At a 72% slope, the predicted loss is 2441.6 tonnes/ha. If we can extrapolate the effect of slope beyond the 18% that Wischmeier and Smith (1978) used in deriving their relationships, then we can also extrapolate the influence of increasing soil organic matter. The second line displays the effect of soil organic matter increasing, concurrently with slope, from 0% O.M. at 0% slope, to 7% O.M. at 72% slope. This pattern is impressive because it suggests that the effect of slope is strongly mitigated by organic matter. In fact, at organic matter contents common in coastal British Columbia soils, soil erosion should not occur even on relatively steep slopes. (Many of our active colluvial soils show very high organic matter contents due to colluvial mixing, and it would be interesting to speculate as to the impact of these very high levels.) The bottom line on the graph shows the effect of organic matter increasing to 16% as slope increases and, quite amazingly, it suggests that at these high organic matter levels and steep slopes there will be no erosion of bare soils. In fact, soil loss will be negative. Clearly, this exercise in extrapolation is not warranted. A cursory examination of the USLE equation (not the nomograph solution) indicates the reason for the result. The value of the K factor for the USLE was determined using the formula (derived from regression analysis):

$$100K = 2.1M^{1.14}(10^{-4})(12-a) + 3.25(b-2) + 2.5(c-3)$$

where M = particle size parameter

a = percent organic matter

b = soil structure code

and c = profile permeability class.

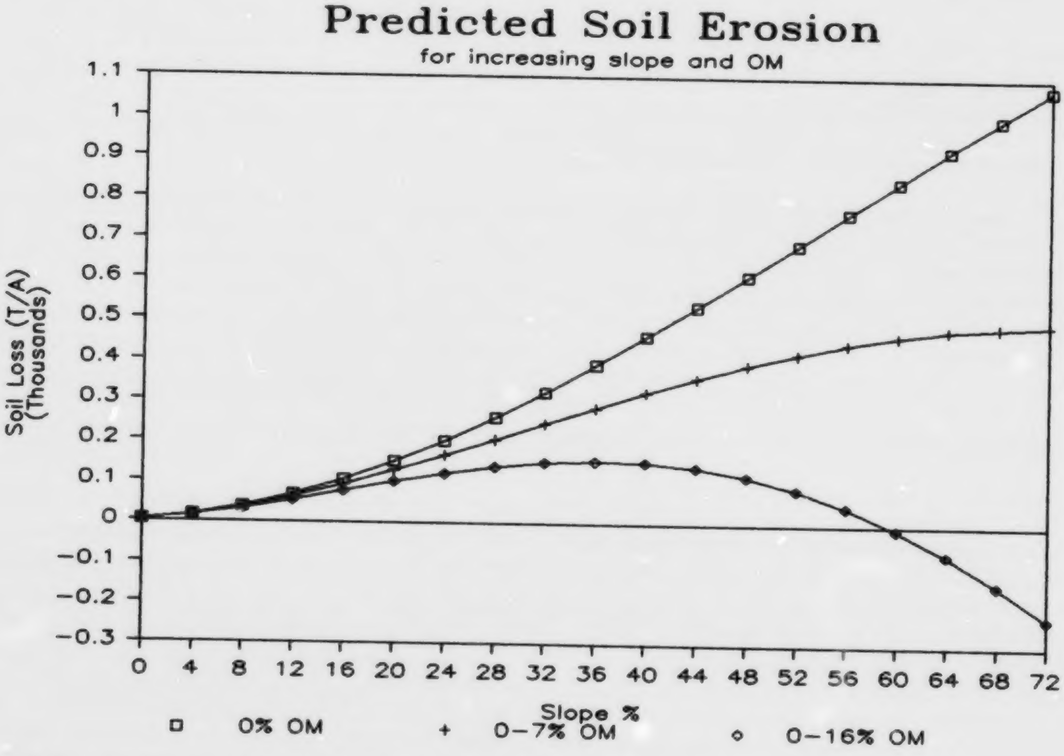

FIGURE 2. Predicted soil erosion for increasing slope and soil organic matter.

The term 12-a is multiplied by the first coefficient of the equation; therefore, values in excess of 12% organic matter yield a negative result. It should be emphasized that the equation was based on data for a maximum of 4% organic matter. Even if we assume that at values greater than 12% there are no additional effects, organic matter levels in excess of 12% change the sign of the K-value and will invalidate the entire USLE.

There is no such obvious reason to place an upper limit on the extrapolation of slope, but it is interesting to note that in the mid 1970's the USDA was publishing tables and graphs based on observational data in the dry interior of the Pacific Northwest, which modified the slope factor of Wischmeier and Smith (1978) (Brooks and Turelle 1974; McCool *et al.* 1976). More recent work, based on plots up to 40% slope in the dry interior Palouse country, tends to support the modification (McCool *et al.* 1982). The modification proposed reduces estimated losses on sites over 9% slope by nearly 50%. The relationships were developed because the conditions in the region differed significantly from the conditions on which the original coefficients were based. This work may represent the only plot data on which we can base slope extrapolations beyond 18%. It has only been partially validated to 38% slopes, and it was done to support evidence of significantly different slope relationships in that specific region. For the same reasons that the modification were proposed, it may not be advisable to apply these modifications to most British Columbia conditions.

5 WHAT CAN WE DO?

It is clear, from the interest in this workshop, that we will be asked to make interpretations on soil degradation. It is also clear that background research and quantitative interpretative models which have been well tested and accepted are rare. What, then, can we do? The first thing is to simplify the problem. Our understanding of the mechanisms controlling soil degradation is not good enough to allow us to make reliable quantitative predictions, but it is often good enough to allow us to rank areas in terms of relative sensitivity to degradation. The second thing we can do is rigorously use and record the results of our powers of observation.

5.1 Identifying Potentially Detrimental Practices

We can use our theoretical and empirical models of degradation processes to identify those conditions that will most probably produce problems. For example, we can use the results of the sensitivity analysis conducted on soil erosion to predict those conditions where we should be most concerned about sheet and rill erosion. It should be clear from Figure 2 that even on steeper slopes, erosion will be minimized so long as high levels of ground cover are maintained. We may predict with some confidence that logging systems such as high-lead or skyline, which minimize ground disturbance, will present a much less serious erosion hazard than systems such as tractor or skidder logging, which expose significant areas of mineral soil. It should also be clear that post-harvesting practices such as scarification or severe slashburning, which expose mineral soil, will promote erosion on sloping ground.

5.2 Identifying Potentially Sensitive Sites

We may also use predictive models such as the USLE to determine whether or not erosion is likely to be a significant form of soil degradation related to forestry operations. Steep, silt loam, colluvial slopes, which are apparently in a steady state condition of additions equalling losses, are a relatively common landform on the west coast of Vancouver Island. These landforms currently support moderately productive stands of western hemlock and Pacific silver fir, but because of active surface creep and dense crown closure, the understory is sparse and the forest floor is discontinuous. The extrapolation of the USLE to these conditions suggests that erosion would be as high as 1100 tonnes/ha per year (a loss of approximately 7.5 cm of available rooting depth) simply as a result of timber removal. This estimate is unreliable (the real value may be less than 50 tons/acre per year or, if we were to reduce understory and forest floor cover through slashburning, greater than 2240 tonnes/ha per year), but it is of a magnitude to suggest that harvesting may shift the balance of accretion and loss to the detriment of these sites. Returning to the suggestion that we use our powers of observation, we should field check logged examples of these landforms to determine whether or not these sites have been degraded. We may consider deferring logging on these sites until the question has been answered.

Slope stability is primarily a water quality concern, but slope failures are also a form of site degradation. Theoretical models (Ballard 1986; Moon [in press]), based on the models of Terzaghi (1950) and Terzaghi and Peck (1967), can be used to identify probable areas of slope instability under any conditions. However, predictions based on these models must be treated with caution because we are unlikely to have all of the information necessary to apply the models. If the limitations are understood, the model can be used to identify areas which may cause problems; if appropriate assumptions are adopted, the model can be used to identify with some confidence those areas unlikely to present problems.

An empirical/taxonomic approach to the same problem can be found in Sondheim and Rollerson (1985). Their approach attempts to identify areas of slope instability based on terrain classifications, and offers an alternative approach. As with all empirical approaches, use of the classes should be restricted to the areas for which they were developed and tested.

5.3 Estimating the Area of Potentially Degradable Land

A useful theoretical model is used by Megahan (1976) to produce tables of geometry for low-standard roads. These tables, or the fairly simple trigonometric formula on which they are based, can be used to estimate a number of the parameters needed to assess the impact of road construction on soil degradation. Given the road width to be constructed, the average expansion of fill material on excavation, the hillslope gradient on which the road is to be built, the cutslope gradient, and the length of road to be constructed, reasonable estimates of total disturbed surface (including cutbank, fillslope, and roadbed) and the slope length of cutslopes and fillslopes can be obtained. These tables, together with a modification of the USLE (Israelson *et al.* 1980), are used by Butt (in press) to estimate erosion loss from logging roads.

Unfortunately, the calculation of slope lengths and areas of disturbance does not answer the question of how much of a road area should be considered degraded or to what degree it has been degraded. At least one other paper at this workshop addresses this question.

6 USING EXISTING DATA BASES TO PREDICT SOIL DEGRADATION

A number of soil, terrain, and biophysical inventories are available, which may provide information relevant to degradation assessment or prediction. Before these data bases are used, a number of steps should be taken:

1) Identify the appropriate predictive models available to answer your question.

2) Determine the data requirements of the models and the sensitivity of the models to changes in the parameters used.

3) Determine whether or not the existing data bases can provide the data necessary to use the model at appropriate levels of precision and reliability, and, if not, whether or not acceptable surrogates of the necessary data are available.

4) If the existing data bases cannot provide the necessary data, determine whether or not the potential errors are acceptable, whether or not the resulting predictions will be useful despite the ambiguities resulting from the use of incomplete data, or if it is feasible to upgrade the existing data base to provide the necessary information.

5) If the potential errors associated with using the existing data base are unacceptable, or if the results are too ambiguous to be useful, then additional data will need to be collected before reliable interpretations can be made.

7 CONCLUSIONS

The preceding discussion has attempted to highlight the characteristics of the models we use to make interpretations. It has attempted to highlight both the advantages and limitations of the various approaches. Theoretical models are the ideal: they can be used to predict response under any circumstances for which we understand the operative mechanisms and for which we can acquire the necessary data. Such models are rare, and theoretical models for which we can acquire the necessary data are rarer. As well, the theoretical model may not fully define the problem; as a result, the theoretical model used may only address part of the problem and the prediction may fail.

Empirical models are more common and can offer useful insights and predictions. Statistically rigorous models are less common and models that have been validated for British Columbia conditions, or with independent data from the same population, are rare. The chief disadvantages of empirical models are the need to acquire large amounts of data to determine confidence levels, the need to restrict their application to the population or boundary conditions for which they were developed, and the danger that correlation may be confused with causality. The last two limitations can lead to serious errors of interpretation when a change in the true causal factors occur and are unrecognized.

For most forms of soil degradation there are neither practicable theoretical models nor empirical models which have been validated for British Columbia conditions. In these cases we are left with either expert systems models or simple expert opinion. We must remember that the operative word is "opinion" and an expert can probably be found to support any position. Our expert systems models and professional judgments should be carefully scrutinized to make sure that they are consistent with those components of the problem for which we have theoretical or rigorous empirical models. Using expert systems models means that the interpretive procedure has been codified and can be reviewed, its assumptions can be evaluated, and its procedures applied or modified by others. Professional judgment offers no such possibility. All three types of model should be viewed with a healthy skepticism, and should be subject to rigorous testing.

Using the types of models described above, we can often identify areas likely to be susceptible to soil degradation. However, I suggested earlier that managers would like to attach economic units to measures of soil degradation and that to do this would require three steps: 1) the quantification of change, 2) the quantification of production or performance loss associated with the change, and 3) the assignment of economic value to the performance loss. We have not, to the best of my knowledge, effectively accomplished even the first step.

We know enough to suggest that there may be serious problems, but we are a long way from reliably predicting the magnitude of change, the performance loss associated with change, or the true economic costs of forest soil degradation. Answering these questions effectively will require the investment of time, money, and effort. They cannot be reliably answered with existing data and available models.

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SESSION 3 PREDICTION/CONTROL

PREDICTION OF FOREST SOIL COMPACTION

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ABSTRACT

The accurate prediction of forest soil compaction is seen as a useful tool in forest management, but the consequences of inaccurate prediction can be serious. Different methods of identifying compactible soils are reviewed here. Predictive models in the literature have incorporated various soil factors, including soil texture, soil moisture, soil strength, initial bulk density, optimum compaction and compression index. Existing models have limited applicability for one reason or another. At the present time, the identification of soils susceptible to compaction is carried out in a subjective and inconsistent fashion. This makes it difficult to justify alternative methods for minimizing soil compaction.

1 INTRODUCTION

The accurate prediction of forest soil compaction would be a useful achievement. If it were possible to identify sensitive soils and the conditions under which they are sensitive, machine operations could be rescheduled to avoid those soils and conditions. Alternatively, we could insist on the use of low ground pressure vehicles or cable systems on compactible soils, if we could be sure conventional ground-based systems would cause unacceptable damage. These restrictions could entail considerable cost to the operator; consequently, it is important to select a predictive method which we can use with a reasonable degree of certainty. Incorrect predictions may carry significant economic consequences as well as loss of professional credibility, not to mention the potential for environmental damage.

In this paper we review some of the methods used to predict compaction. We then comment on the effectiveness of prediction as a method to avoid or minimize compaction. In considering compaction, we are interested in the alteration of the physical properties of the soil caused by the impacts of tracks and wheels (not blades). We are not considering the more general term "site disturbance", which includes scalping, gouging, and exposure of mineral soil. Compaction implies a volume change, with attendant increase in bulk density. Machine operation on wet soils may not cause significant density change. It will, however, lead to structural deformation, in the form of puddling and rutting. Such structural deformation should ideally be considered along with compaction in any predictive method.

2 STUDIES IN BRITISH COLUMBIA

Although numerous studies carried out in the Pacific Northwest of the United States have testified that forest soil compaction is a real problem, few such studies have taken place in this province. No one has adequately addressed the question: What is the nature and extent of soil compaction, and is the problem of sufficient gravity to warrant effort to minimize it? This should be the first question we ask ourselves.

Bockheim *et al.* (1975) determined that tractor-logging in southwest British Columbia could disturb as much as 90% of the area logged, with up to 60% of the disturbed area considered "deep". How much of this disturbance produced measurable compaction is not known. Smith and Wass (1979, 1985) have been active in studying the nature of bladed and compacted skid trails and their effect on tree growth in southeast and central British Columbia. On most skid trails, tree growth was depressed in comparison to that in equal-aged trees in adjacent undisturbed soil, but some skid trails yielded superior growth (Smith and Wass 1979). Packee (1969) found that tree height growth on bladed skid trails in young plantations on southern Vancouver Island was 28-38% less than that on non-roaded portions of the harvested area. This amounted to a volume loss of 50 m^3 ha^{-1}. More recently, Rollerson and Kennedy examined the effect of a skidder equipped with low ground pressure tires on forest soils on Vancouver Island.[1] On two of three sites, they found average increases in bulk density to be so low as to be insignificant (they believed) to tree growth. On the third site, logged during wet weather, increases in bulk density on main skid trails were much higher. The high natural variability in bulk densities made conclusive statements impossible. Some work on compaction is currently being carried out by the Ministry of Forests in the Prince George Region,[2] but, clearly, an inadequate number of studies have dealt with the nature and extent of the problem in British Columbia. For the purposes of this paper, we assume compaction is a significant form of soil degradation and that prediction might be a worthwhile endeavor.

2.1 Predicting Compaction

Early attempts to measure, understand, and predict soil compaction were confined to the agricultural sector (e.g., ASAE 1971). However, the development of physical theories surrounding machine-soil interactions was very much stimulated by research into off-road trafficability problems, mostly in military applications (Department of the Army 1959; Bassett *et al.* 1966). Agricultural engineers were instrumental in adapting this body of knowledge to the analysis of compaction *per se* (rather than trafficability) (e.g., Vanden Berg *et al.* 1957; Soehne 1958). This eventually led to the development of a range of predictive models spanning the spectrum between deterministic (e.g., Soehne 1958) and empirical (e.g., Braunack and Dexter 1978; Raghavan and McKyes 1979).

Compaction of forest soils was recognized relatively early (e.g., Steinbrenner 1955; Lull 1959). Many subsequent studies have documented the degree and extent of compaction associated with different machine systems and different soils, but few, until recently, have made an attempt to relate compaction to soil properties systematically. The resultant lack of hard and comparable data sometimes led to conflicting statements as to what constitutes a "compactible soil". A number of soil properties have been proposed as important factors which may have predictive value.

2.2 Texture

According to Pritchett (1979, p. 112): "...use of heavy machinery...while soils are wet, will increase bulk density, particularly of fine textured soils". Later, in the same book, he states: "Medium textured soils (loam and silty loam) appear to compact to greater densities than fine or coarse-textured soils" (p. 323). Hatchell *et al.* (1970) found that final bulk densities of machine-compacted forest soils were positively correlated with percent silt, and negatively correlated with percent clay. Diebold (1954) rated well-graded soils of coarse texture or medium-textured soils with less than 40% silt as those most susceptible to compaction. Grain size distribution has frequently been cited as an important factor (Diebold 1954; Chancellor 1971), in that well-graded soils have a higher maximum compacted density than poorly graded ones, although they may require a greater compactive energy to achieve it. Most soil scientists would agree that, other factors being equal, well-graded and/or medium-textured soils are more susceptible to compaction than poorly graded soils and/or fine and coarse ones. The problem with forest soils is that these other factors commonly are not equal. A thorough review of the literature on forest soil compaction revealed no consistent relationship between soil texture and degree of compaction. Texture, by itself, cannot be used to predict compaction.

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[1] Rollerson, T.P. and C.P. Kennedy. 1984. Compactive effects of a low ground pressure skidder. Woodlands Services, MacMillan Bloedel Ltd., Nanaimo, B.C. Unpubl. report.

[2] See Poster Presentations by McLeod and McLeod and Hoffman in this volume.

2.3 Soil Moisture and Soil Strength

Soil moisture content has frequently been cited as a major factor in compactibility (Miles *et al.* 1981), even to the extent of outweighing the variable effects of vehicle loading characteristics (Lull 1959). The USDA Forest Service has restricted the use of logging machinery when soil moisture exceeds a critical value (Miles *et al.* 1981).

Soil moisture is the most important factor affecting strength at a specified density (Chancellor 1971). Wet soils are weak soils and, thus, have a greater probability of yielding under imposed stress. Several researchers have suggested that the relationship between soil moisture (in particular, tension) and soil strength may form an appropriate basis for predicting compaction susceptibility or trafficability. Here in British Columbia, Paul and de Vries (1979a,b) found a linear relationship between soil strength, as measured by a cone penetrometer, and soil moisture tension in three Lower Fraser Valley agricultural soils. They suggested that there was a critical water table level (and corresponding soil moisture tension) beyond which soil strength is inadequate to resist compaction, sinkage, and excessive wheel slip. Given soil moisture tension (or, under equilibrium conditions, water table depths), soil strengths could be predicted with reasonable accuracy, if certain empirical parameters were obtained.

Froehlich *et al.* (1980), for example, prepared an empirical model for predicting forest soil compaction, in which (i) the number of vehicle passes, and (ii) a cone penetrometer index of soil strength explained the largest proportion (54%) of the variation of bulk density change. Other soil factors, including machine-derived pressure, soil organic matter content, initial soil density, and soil moisture content, together added only 14% to the final coefficient of determination of their predictive equation. However, the effects of some of these factors are probably contained within the cone penetrometer index of strength. This model was used, with some success, to predict compaction on four residual soils in the Sierra Nevada of Northern California.

The use of a cone penetrometer, or a similar method of indexing soil strength, certainly holds promise for predicting compaction on forest soils in British Columbia. A certain amount of research would be necessary to produce a predictive method for British Columbia, since a different combination of factors is probably effective in our glacially derived soils. However, use of derived indices of soil strength has some drawbacks; determinations must be made for each soil type over a range of moisture contents. The inherent variability in field soil strengths is unknown for British Columbia soils, and necessary sampling densities may be excessive. Furthermore, soil strengths usually increase with compaction. Compacted density represents the point at which increased strength just matches the applied force; but, the rate of strength increase with compaction may be quite different depending on the soil type and other factors. Finally, pedologists seem to feel that practical use of a cone penetrometer in till or colluvium-derived soils would be limited by stoniness. We believe this may not be a serious limitation on many lower elevation soils which will be subject to ground skidding; cone penetrometers, as indicators of soil strength, could be useful in site-specific assessment of compaction susceptibility and trafficability.

2.4 Initial Bulk Density

A review of the literature suggests that initial soil bulk density may serve as an indicator of potential compaction. Figure 1 indicates an increasing degree of compaction with decreasing initial bulk density. As bulk density and bearing strength are related, this relationship is not surprising. The scatter in the plot is in part a function of different sampling methodologies, yarding equipment, soils, and soil moisture conditions.

Unfortunately, despite the empirical relationship suggested by Figure 1, initial bulk density by itself cannot be used to predict compaction. Light soils are not necessarily weak soils and, moreover, certain light soils may experience increased strength with densification at the same rate as heavier soils (Froehlich and McNabb 1983). In one particular study, Froehlich *et al.* (1980) found that initial bulk density added little explanation of the variability of compacted density.

2.5 Optimum Compaction

A number of researchers, particularly in the agricultural sector, have focused on laboratory tests measuring optimum or "Proctor" compaction. These tests rate the compactibility of materials for engineering use, and involve the application of specified stresses on a soil sample over a range of moisture contents. The compacted density of the sample increases with moisture content up to a certain point, then decreases again (Figure 2). At moisture contents lower than this point, soil particles resist reorientation due to matric forces and inadequate lubricating action. At moisture contents above the optimum, compacted density becomes limited by the volume of pore water, which is more or less incompressible. The moisture content at which optimum compaction takes place, corresponds approximately to 80% saturation (Hillel 1980). The curve shifts up and to the left (i.e., greater compacted densities at lower moisture contents) as the compacting stress increases. Thus, both optimum compaction and its corresponding moisture content are sensitive not only to a range of soil properties, but also to the magnitude of the applied stress.

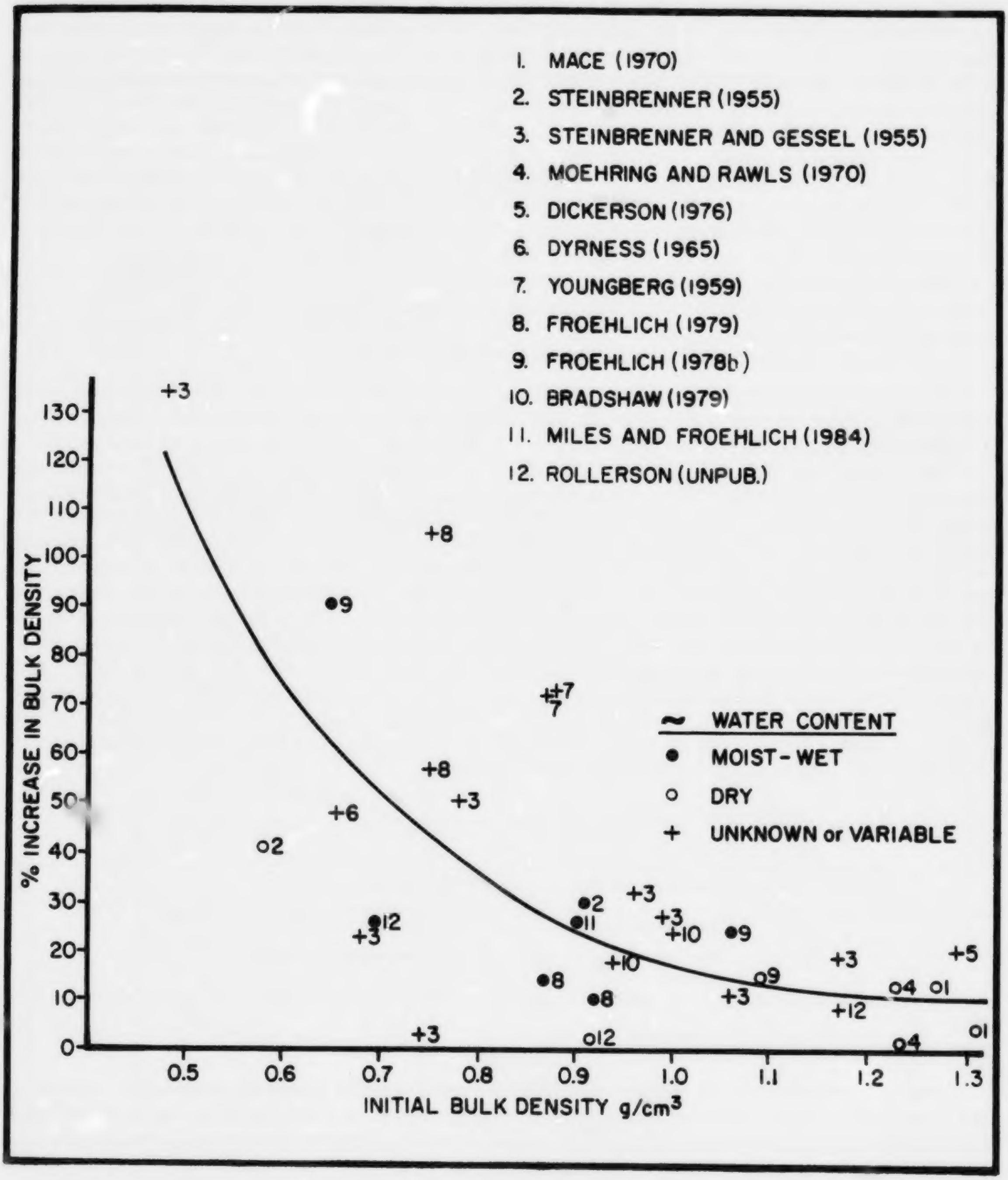

FIGURE 1. Maximum % increase in bulk density recorded versus initial density for surface soils (the depth intervals sampled are not always comparable among studies nor is the degree of use).

In eastern Canada, Raghavan *et al.* (1976) used a converted Proctor compaction test to index and predict the compactive behavior of certain agricultural soils, with reasonable accuracy, under a wide range of moisture contents. Inspired by the apparent success in the agricultural sector, some investigators have applied the concept to predicting compaction in forest soils. Howard *et al.* (1981) suggested that one index of the susceptibility to compaction is the final compacted density achieved in a laboratory-based, modified compactive test. They reasoned that the higher the density achieved in the test, the more compactible the soil. Accordingly, they compared the optimum compaction of 14 forest and range soils in California. Regression equations were developed, which predicted laboratory-compacted densities on the basis of soil properties. Organic carbon was the single factor most highly correlated (negatively) with compacted density, suggesting that soils rich in organic matter are relatively resistant to compaction. They also examined the moisture characteristic curves of their sample soils to determine where field capacity is placed in relation to the derived moisture content for optimum compaction. Soils draining to field capacities well below the optimum moisture contents were considered low risk for compaction, whereas soils in which field capacity is at or near the optimum were rated highly susceptible. Soils were rated as to compactibility according to the probable length of time that their field moisture content is near to optimum, assuming that maximum compaction will take place at that point.

This may not be a good assumption. The standard ASTM compactive test (ASTM 1982) involves 75 blows from a 2.5-kg hammer falling 30.5 cm. This almost certainly overestimates actual compactive stresses applied by logging equipment. Sidle and Drlica (1981) found, in one case, even a 10-blow version of the test overestimated field bulk densities after 150 skidder turns. Froehlich *et al.* (1980) discovered that the standard test overestimated skid trail densities by 24-29%, thus underestimating the corresponding optimum moisture content. They found that a modified test, utilizing only 8% of the compactive stress of the standard Proctor test, gave reasonable approximations of field densities after 20 round-trip passes with logging machines. More importantly, the compactive behavior of some soils, at those lower stresses, differs from that at higher stresses. Some soils exhibit relatively flat moisture-density curves, and can be thought of as moisture-insensitive (Froehlich and McNabb 1983). These include uniformly or poorly graded coarse-textured soils, and fine-textured cohesive soils with non-expanding clay minerals. Moisture-sensitive soils include well-graded coarse soils and fine-textured soils with expanding 2:1 clay minerals. The Unified Soil Classification System may serve as a basis for separating moisture-sensitive from moisture-insensitive soils. Table 1, based on information presented by Froehlich and McNabb (1983), provides a tentative classification. Distinguishing the two groups of soils is useful, since moisture-insensitive soils may compact equally at any moisture content.

TABLE 1. Characteristics of moisture-sensitive and insensitive soils

Moisture-Sensitive	Moisture-Insensitive
Well-graded coarse	Poorly graded coarse
Fine with 2:1 clay minerals	Fine with non-expanding clay

2.6 Compression Index

The compression index (C) has also been proposed as a basis for predicting compaction. This index, like Proctor compaction, has been borrowed from soil mechanics. It is defined as the slope of the linear portion of the virgin compression curve (VCC), which in turn describes the relationship between bulk density (or void ratio) and the logarithm of the applied stress (Figure 3). Theoretically, each unconsolidated natural soil exhibits its own particular VCC and, hence, C. In other words, each soil will experience a particular increase in density (or reduction in void ratio), with a specified increase in applied stress.

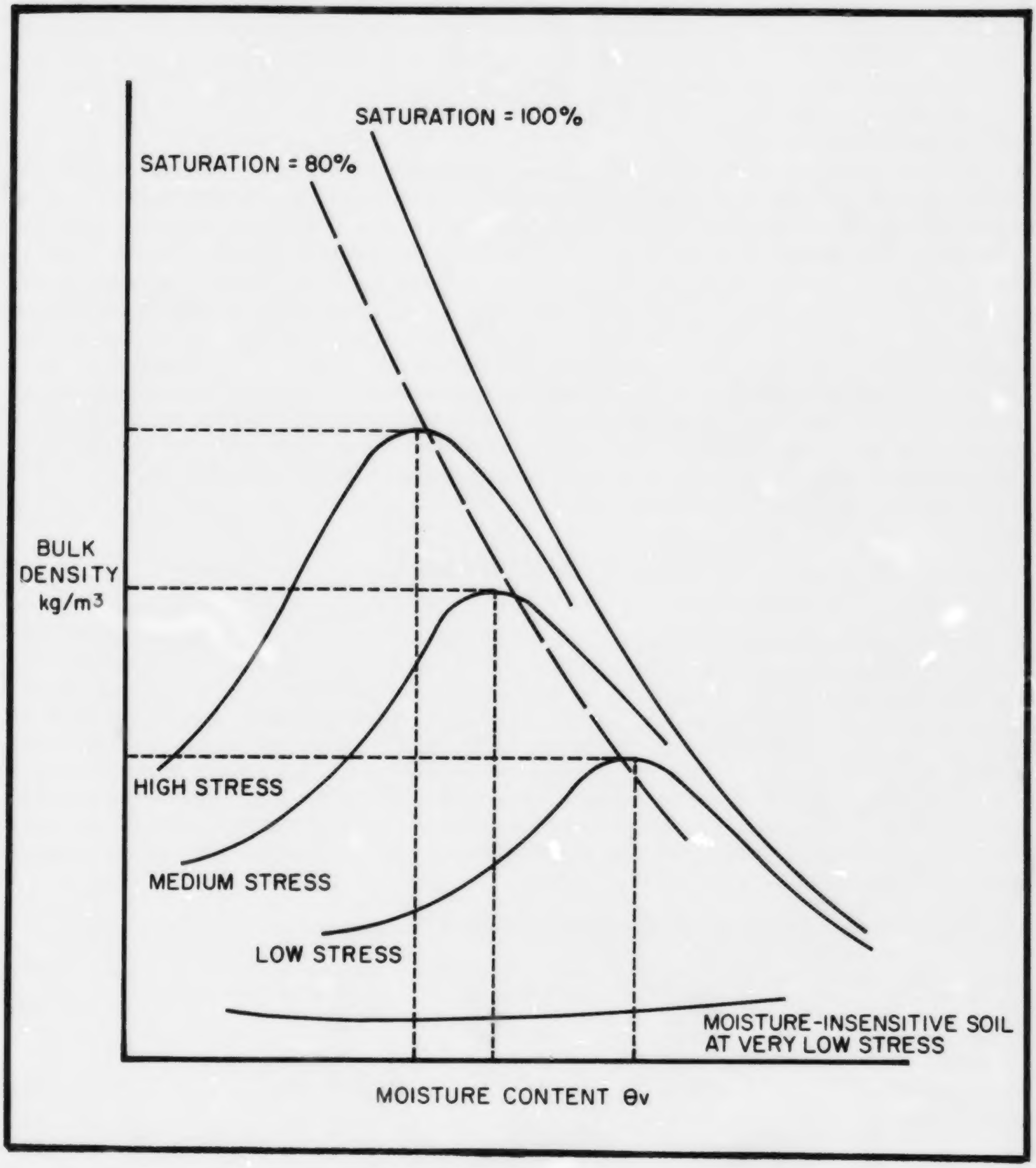

FIGURE 2. Soil moisture/density curves for a hypothetical soil at three levels of applied stress.

Larson *et.al.* (1980) examined the compression indices from eight soil orders in the USDA Soil Taxonomy (Soil Survey Staff 1975). They derived models using C to predict compactive behaviour in agricultural soils. The model suggests that the greater the value of C (i.e., the steeper the VCC), the greater the resultant density change for a given increase in applied stress. Can C be used to predict compaction in forest soils? No. In reality most soils have a compression curve in which only a small segment is linear. The slope of that linear segment may not be representative of the soils compressive behaviour under field conditions. Furthermore, the complexity of the stress applied by logging machinery may produce compression curves quite different from those shown in Figure 3. For example, the compressive behaviour of a poorly graded sand will be different under a vibrating load than under a static load. As we have seen, laboratory tests that do not closely mimic the complexity of field conditions and real stresses have limited usefulness.

Furthermore, the complexity of the stress applied by logging machinery may produce compression curves quite different from those shown in Figure 3. For example, the compressive behavior of a poorly graded sand will be different under a vibrating load than under a static load. As we have seen, laboratory tests that do not closely mimic the complexity of field conditions and real stresses have limited usefulness.

Nonetheless, if we define compactibility as the percent increase in density under a given increase in applied stress, then C may be a parameter of some utility. Larson *et al.* (1980) showed that clay content could explain as much as 90% of the variation in C, and that the correlation was positive. The obvious implication is that clay-rich soils are compactible. Other studies (Soane *et al.* 1972; Howard *et al.* 1981) have found a strongly negative correlation between clay content and compaction. The apparent contradiction lies in the definition of compaction. Larson *et al.* (1980) were interested in the relative change in bulk densities; the others were interested in final compacted density. Many clay-rich soils will compact faster (along the linear portion of the VCC), but to lower ultimate density. Therefore, they have different relative compactibilities according to the definition used.

3 DISCUSSION

The foregoing illustrates a problem in predicting compaction. Is it more important to know the final density or the percent increase over the initial density? A number of researchers have suggested that threshold densities exist, above which root growth is inhibited or prevented. The predicted compacted density in relation to this threshold value could conceivably be a meaningful way of assessing potential effects on productivity. It has been widely quoted that 1400 kg m^3 or 10% aeration porosity are critical limits at which root growth becomes significantly impaired, and that growth does not continue at densities above 1800 kg m^{-3} (e.g., Gent *et al.* 1983). However, relevant studies do show a high variability in threshold values. Table 2 summarizes the various threshold values for selected western tree species. These values vary according to species, soil type, and other factors (Froehlich and McNabb 1983), to a degree which cannot yet be predicted.

TABLE 2. Threshold bulk density values for selected western tree species

Reference	Species	Soil	Threshold (kg m^{-3})
Forristall and Gessel (1955)	Douglas-fir	Till-derived	1250
	western redcedar		1800
Minore *et al.* (1969)	Douglas-fir	SL	1450-1590
Heilman (1981)	Douglas-fir	L	1830
		L	1750
		SL	1750

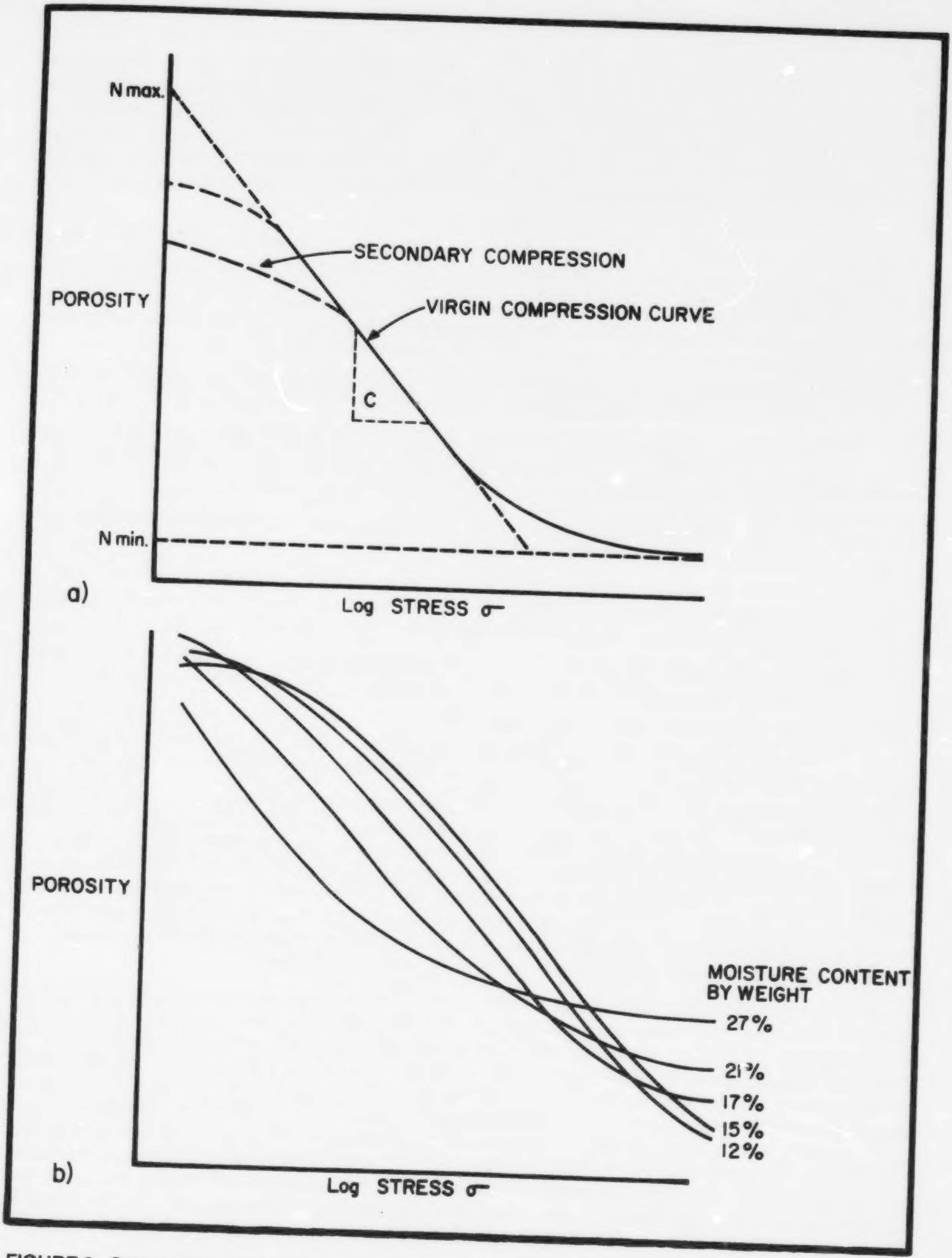

FIGURE 3. Stress-strain relationships; a) components of curve (after Larson *et al.* 1980); b) family of curves at different moisture contents.

When expressed as a percentage increase in bulk density, compaction seems to have a more consistent effect on plant growth. Foil and Ralston (1967) found a linear relationship between decreasing root weight and increasing bulk density between certain limits. Froehlich and McNabb (1983), assembling data from four studies covering three species and six soil types, showed a nearly linear reduction in height growth with percent increase in bulk density. Accordingly, it should be preferable to predict the percent change in bulk density (or percent decrease in aeration porosity), rather than the ultimate compacted density.

Unfortunately, no method of predicting compaction can actually do so with any degree of certainty. Even rating soils according to their relative susceptibility is difficult. Nevertheless, we can make a number of general (if somewhat vague) statements with confidence:

1. Well-graded soils will compact more easily and to a progressively greater density as optimum moisture contents are approached, than will poorly-graded soils;
2. Poorly-graded soils and fine-textured soils with non-expanding clay minerals will experience moisture-independent compaction (Table 1);
3. Very coarse or fragmental (clast supported) soils will resist compaction because an applied stress will be borne on interlocking stones, cobbles or gravels. Skeletal (CSSC 1978) soils in which coarse fragments are not interlocking may not resist compaction;
4. Clay-rich soils may compact at a faster rate, but to a lower ultimate density, than clay-poor soils under a given stress (Larson *et al.* 1980);
5. Fine-textured forest soils have a high probability of retaining a moisture content at or above the optimum for compaction. They will, therefore, be more susceptible to structural damage under field conditions, than will more rapidly draining soils (Howard *et al.* 1981);
6. Soils with initially low bulk density will tend to experience a greater relative density change under a given stress than soils of higher bulk densities (Figure 1); and
7. The compaction of wet soils is limited by the volume of pore water, which is more or less incompressible under the conditions experienced in modern logging. However, structural damage associated with puddling and rutting may substantially reduce site productivity.

It must also be understood that factors other than soils can have a significant influence on the degree of compaction induced by a logging operation, and consequently, complicate the question of predicting compaction. For example, the logging of an area proceeds over a period of time extending from weeks to months. Soil moisture conditions, and their consequent effect on compaction, can vary significantly during this time; e.g., frozen soils can thaw, snow can come and go. The amount of slash present in an opening, which may act to partially support yarding equipment and so disperse wheel loads, can vary dramatically. Timber volumes to be yarded can range from 150 to as much as 1000 m^3/ha, influencing substantially the number of trips a skidder or forwarder may make across a given piece of terrain.

The homegeneity or heterogeneity of the terrain itself may influence where a machine can go and, therefore, how much compaction occurs. On level terrain a skidder may equally affect all areas; on hummocky or ridged terrain the machine may be severely limited in where it can and cannot go, thereby concentrating impacts. A machine operating on an adverse grade (uphill) may not be able to skid or forward as large a load, and so may require more return trips than the same machine operating on a level or favorable (downhill) grade. Yarding on an adverse grade may also result in more wheel spin with a consequent increase in compaction or rutting. The machine or machine mix used to fell and yard an area can vary significantly, as can the form in which the trees leave the area. Simply changing from a line skidder to a grapple skidder can modify the pattern of skid roads and the distribution and degree of compaction substantially. Log size can vary from whole trees in a feller buncher-skidder operation, to 7 or 8 m in a harvester-forwarder operation. In the first case, the trees are dragged behind the skidder; in the second, carried off the ground.

Studies of compaction have focused on the mineral portion of forest soils. Complicating this picture, particularly on the coast, are varying forest floor depths. On Vancouver Island, the LFH can range from 2 to 5 cm deep on well-drained, east coast sites, to well over 0.5 m on some west and north coast sites. In some of these soils, the forest root network is contained almost entirely within the forest floor; compaction of the mineral soil may then be an irrelevant question.

4 CONCLUSIONS

The prediction of compaction on forest soils is only one of a number of options for reducing its severity and extent. Other possibilities include minimizing skid trail length by careful planning (Froehlich *et al.* 1981), rehabilitating compacted soils through the use of tillage implements (Andrus and Froehlich 1983), winter logging over snow and frozen ground, or using low ground pressure equipment. However, it may be difficult to justify the implementation of more expensive harvesting options, unless an unacceptable amount of damage is anticipated under conventional harvesting methods.

Anticipation of soil damage is now based on broad perceptions of compaction susceptibility. For example, moist fine-textured soils are widely believed to compact to a greater extent than well-drained coarse soils, under a given stress. The identification of susceptible soils is now carried out in a subjective and inconsistent fashion. Until adequate predictive models become available for forest soils in British Columbia, the present system must suffice.

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SESSION 3 PREDICTION/CONTROL

QUANTITATIVE DEFINITIONS OF STABILITY CLASSES AS RELATED TO POST-LOGGING CLEARCUT LANDSLIDE OCCURRENCE

PART II

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ABSTRACT

Slope stability following clearcutting is examined in the Norrish-Cascade watershed, using a terrain evaluation method developed over the past five years. The polygons of a surficial geology map are placed into terrain classes, which are defined by factors identified from a detailed landslide survey; each of these classes is assigned to one of four stability classes based on a clearcut-related, slides-per-clearcut hectare criterion. Other terrain class statistics include the number of natural slides per hectare, the probabilities of both natural- and clearcut-induced slope failures occurring in a polygon, the ratio of these probabilities, and the ratio of the clearcut and natural rates on a per-hectare basis. The study outlines the general methodology, discusses these statistics, and describes a stability rating map based on 15 detailed terrain classes. This classification is compared to three simpler ones, and the form stability classes are generalized to two. The ratio of clearcut-related slides per hectare to natural slides per clearcut hectare was 2.0 for the entire study. No relationship was evident between this ratio and the stability class ratings for any of the classifications. Positive relationships were found between the probability of clearcut-induced failure occurring within a polygon and the number of clearcut slides per clearcut hectare. As well, high probabilities of clearcut failure were generally associated with high probabilities of natural failure.

1 INTRODUCTION

This paper presents (1) a brief summary of the approach and results from a case study in which a terrain evaluation method for assessing clearcut landslide activity following forest harvesting was applied, and (2) a comparison of these results to the results from three simpler classifications.

The terrain evaluation method used in this study has evolved over the past five years by contributions from several interested earth scientists. One of the basic concepts of the method, proposed at the British Columbia Slope Stability Mapping Workshop (Howes 1982) requires that a detailed landslide inventory survey be conducted in conjunction with a surficial geology mapping programme and that the detailed landslide site data and area surficial geology data be integrated to identify specific terrain susceptible to clearcut landslides. The paper also outlined an initial framework for collecting, integrating, and presenting the different data sets. Parts of this method were applied to an area on the mid-coast of British Columbia (Townshend 1982). In this study, the surficial geology units identified during the mapping programme were grouped into unique terrain classes based on factors identified from observations of landslides in the area. Although each class was assigned a qualitative slope stability rating from an earlier rating scheme

(Bourgeois 1974), it was the first application of defining terrain classes defined from a landslide study. The method was also applied to a few small clearcut blocks on the west coast of Vancouver Island (Rollerson 1984), and the results were outlined at the Ninth B.C. Soil Science Workshop (Sondheim and Rollerson 1985). This study was significant because it introduced into the method a quantitative technique for assessing potentially unstable terrain, which involves the calculation of landslide frequency rates on a unit area basis for different terrain classes, which, in turn, are assigned a rating from a predefined slope stability rating system. Certain aspects of the method, such as assessing natural landslide rates and the production of a landslide inventory map, were not undertaken in either of these studies, however, a detailed summary of the method is in preparation.[1] Further discussions of various aspects of the method may be found in papers by Rollerson and Sondheim (1985) and Rollerson *et al.* (1986).

The case study examined 15 609 ha of the Norrish, Cascade, and Deroche river valleys, an area of multiple resource use located 65 km east of Vancouver, British Columbia. Of basic interest was the identification of terrain subject to slope failure and the impact of tree harvesting on the rate of slope failure for long term resource management. A terrain-landslide study was initiated in 1984 to address this topic.

The mapping associated with the case study was based on aerial photographs and fieldwork, during which approximately 35% of the 933 terrain mapped polygons were visited on the ground. Detailed descriptions of each polygon were collected, from either on-site inspection or photo and contour map interpretation (for details see Howes, in prep.[2]). Because of the expense of this kind of approach, it was of interest to estimate how different the final results would have been if much less detailed data were available. This issue is now particularly pertinent in light of the availability of Thematic Mapper satellite imagery and the commencement of a provincial 1:20 000 programme to collect digital topography for all of British Columbia. Another issue of interest involves the extent to which results derived from one geographic area can be applied to another.

2 DEFINITION OF TERMS

The terms "landslide" and "slope failures", in this paper, refer to the downslope movement (slow to rapid) of a shallow mass of non-consolidated material by sliding and/or flowing and include debris slides, debris flows, and torrents (Sharpe 1938; Varnes 1958; Swanston 1974). Only those landslides with an area of 200 m^2 were used in the study. Clearcut-induced landslides refer to those landslides that initiated within clearcut areas, whereas natural landslides refer to those that occurred in a natural setting. Landslides resulting from road activities are not considered in this paper. Rapid drainage, as used here, includes the rapid and well-drained classes of the System of Soil Classification for Canada (Agriculture Canada 1974). Moderate drainage includes the moderately well and imperfectly drained classes of the same system.

3 PHYSICAL SETTING

The Norrish, Cascade, and Deroche river valleys are situated on the north side of the lower Fraser Valley and are part of the Southern Coast Mountains of British Columbia. Except for the Deroche drainage basin, which is made up of Jurassic meta-dacites and meta-andesites, the area is underlain by granodiorite and quartz diorite rocks of the Coast Plutonic Rocks (Roddick 1965). The valleys have been subject to multiple Pleistocene glaciations and were completely buried by ice during the most recent glaciation, the Fraser Glaciation (Armstrong *et al.* 1965). Fraser ice smoothed and rounded the bedrock peaks and ridges between the drainage basins and deposited a thin and, in places, discontinuous mantle of till. Erosion by the ice also oversteeped the valley sidewalls. The upper portions of these side slopes consist of thin mantles of till and/or colluvium (formed in postglacial time) with the occasional outcropping of bedrock. Lower slopes commonly consist of thicker deposits of till. Thick deposits, up to 30 m deep, of glacial and glaciofluvial sediments (sand, gravel, silt) and till are distributed along the valley bottoms. Most of these deposits formed during the deglaciation of Fraser ice and have subsequently been dissected in postglacial time by streams to form multi-level terraces. Escarpments of these materials adjacent to present-day stream channels are an important contributing source of sediment to the streams. Alluvial fan accumulation and mass movement processes also commenced during postglacial time and continue today. Fans are being built-up where steep tributary streams debouch into the main valleys, particularly in the Norrish River basin, and various types of mass movements (rockfall and slides, debris slides, slumps) occur on the oversteepened valley sidewalls.

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[1] Howes, D.E. In prep. A method for predicting terrain susceptible to landslides following forest harvesting: a case study from Southern Coast Mountains, British Columbia. B.C. Ministry of Environment and Parks, Recreational Fisheries Branch, Victoria, B.C.

[2] Ibid.

The area is presently characterized by cool, wet winters and temperate summers. Annual precipitation, based on records from Mission West Abbey (221 m as l), is 1771.1 mm, with 69% of it falling between the months of October through March (Atmospheric Environmental Service 1981). Intense storms frequently occur during the winter months as reflected by one-day and three-day extreme precipitation totals of 92.6 and 123.0 mm, respectively, for a 10-year return interval (Atmospheric Environmental Service 1982; Coligado 1982) and are thought to be one of the causative factors influencing initiation of landslides (for example, see Swanston 1974).

4 THE METHODOLOGY AND ITS APPLICATION TO THE STUDY AREA

The following is a brief description of the terrain evaluation method applied to the Norrish-Cascade terrain and landslide study (for details, see Howes, in prep.[3]). The method consisted of six steps:

1. mapping the surficial geology using the Terrain Classification System (ELUC 1976; Ryder and Howes 1984) to define homogeneous areas with respect to material, texture, surface expression and process; additional data, such as slope, aspect, and bedrock type for each terrain unit (polygon), was also obtained from topographic and geologic sources;
2. collecting and analyzing the landslide site data to identify factors contributing to clearcut landslides; factors identified after analysis included surficial material, "critical" slope angles for different material types, slope configuration, drainage, depth of material and presence/absence of gully erosion (Table 1);
3. defining a set of terrain classes (in this case, 15 were required) based on these factors such that each terrain polygon can be assigned to one and only one class; each terrain polygon was then categorized according to this new terrain classification;
4. calculating for each new terrain class several stability statistics (based on data obtained from the landslide and terrain programs) related to both natural and clearcut failures (Table 2);
5. grouping the terrain classes into four stability classes based on the ratio of the number of clearcut-induced slides to the number of clearcut hectares;
6. producing a computer-generated map displaying the polygons labelled according to the stability class and other criteria of interest (Fig. 1).

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[3] Ibid.

The terrain class statistics are derived from the following variables:

NP(i) - the number of polygons in class i;

NPC(i) - the number of polygons in class i which are partially or completely clearcut;

NPN(i) - the number of polygons in class i which are partially or completely in a natural state;

NPCF(i) - the number of polygons in class i which contain one or more failures in clearcuts (and which are assumed to be associated with the clearcutting);

NPNF(i) - the number of polygons in class i which contain one or more natural failures;

NCF(i) - the number of clearcut-related failures in all polygons in class i;

NNF(i) - the number of natural failures in all polygons in class i;

AC(i) - the clearcut area (ha) in all polygons in class i between 1962 to 1981;

AN(i) - the natural area (ha) in all polygons in class i as of 1962;

A(1) - the total area of all polygons in class i.

From these variables the following terrain class statistics were calculated:

PCF(i) = NPCF(i)/NPC(i),

PNF(i) = NPNF(i)/NPN(i),

RFAC(i) = NCF(i)/AC(i),

RFAN(i) = NNF(i)/AN(i),

RPCN(i) = PCF(i)/PNF(i),

RACN(i) = RFAC(i)/RFAN(i),

SC(i) = 1 if RFAC(i) < 0.01, a rating of "low";

= 2 if $0.01 <$ RFAC(i) < 0.05, "low to moderate";

= 3 if $0.05 <$ RFAC(i) < 0.10, "moderate";

= 4 if RFAC(i) > 0.10, "high".

where PCF(i) is the probability of post-logging failure occurring within any given polygon (containing clearcuts) in class i; PNF(i) is the probability of natural failure occurring within any polygon (containing natural areas) in class i;

PNF(i) is the probability of natural failure occurring within any polygon (containing natural areas) in class i;

RFAC(i) is the ratio of clearcut-related failures to clearcut area (ha);

RFAN(i) is the ratio of natural failures to natural area (ha);

RPCN(i) is the ratio of the probability of clearcut-related failure to the probability of natural failure, on a polygon basis, for class i;

RACN(i) is the ratio of clearcut to natural failure rates on a per-hectare basis, for class i;

SC(i) is the stability class or stability rating for class i, based on the RFAC statistic.

Explanation of Map Notation

Natural mass movement rating (see **A**) — • 3+ : H-L — Clearcut landslide rating (see **B**)

Potential Introduced landslide debris rating (see **C**)

This symbol indicates that (1) natural landslides have occurred within this polygon (• symbol); (2) there is a moderate likelihood that rapid mass movements and/or slumps will occur following clearcut operations (3 + symbol); and, (3) if a landslide should occur, there is a high likelihood that the landslide debris will impact upon the stream system and possibly, be deposited into a lake (H-L symbol).

A NATURAL MASS MOVEMENT RATING

Symbol	Description
•	Indicates that at least one or more shallow rapid mass movements and/or slumps in unconsolidated material in a natural setting has initiated within the polygon.

B CLEARCUT LANDSLIDE RATING

Symbol	Description
4	Terrain polygons that have a high likelihood of clearcut rapid mass movements occurring following clearcut operations (≥0.100 failures per hectare).
3	Terrain polygons that have a moderate likelihood of clearcut rapid mass movements occurring following clearcut operations (≥0.05 to <0.100 failures per hectare).
2	Terrain polygons that have a low likelihood of clearcut rapid mass movements occurring following clearcut operations (≥0.010 to <0.05 failures per hectare).
1	Terrain polygons that have a very low likelihood of clearcut rapid mass movement occurring following clearcut operations (<0.0100 failures per hectare).
+	Terrain polygons that have a moderate likelihood of clearcut slumps occurring following forestry operations (≥0.05 to <0.10 failure per hectare).

C POTENTIAL INTRODUCED LANDSLIDE DEBRIS RATING

Potential introduced landslide debris is a qualitative rating of the likelihood of clearcut landslide debris entering the stream system if a landslide should occur within a terrain polygon. The stream system includes stream order one and two channels, and gullies.

H	There is a high likelihood of landslide debris impacting upon the stream system, if a clearcut landslide (i.e. rapid mass movement, slump) should occur in these terrain polygons. (Most of the clearcut rapid mass movements and slumps occurring in these areas are expected to impact upon the stream system).
M	There is a moderate likelihood of landslide debris impacting upon the stream system, if a clearcut landslide (i.e. rapid mass movement, slump) should occur in these terrain polygons. (Some of the clearcut rapid mass movements and slumps in unconsolidated materials occurring in these areas are expected to impact upon the stream system).
L	There is a low likelihood of landslide debris impacting upon the steam system, if a clearcut landslide (i.e. rapid mass movement, slump) should occur in these terrain polygons. (Few of the clearcut rapid mass movements and slumps occurring in these areas are expected to impact upon the stream.)
-L	This symbol is used to modify the potential introduced landslide debris rating and indicates that landslide derived debris may be deposited into a lake.

▨	Terrain polygons covered by this pattern represent those areas that have a clearcut landslide rating of 4 and a potential introduced landslide debris rating of H (High) or M (Moderate), or areas that have a clearcut landslide rating of 3 and a potential introduced landslide debris rating of H (High).

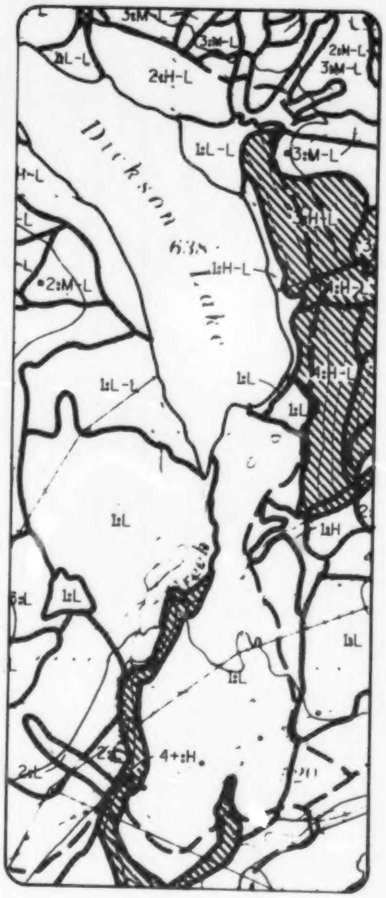

FIGURE 1. Example of part of the Clearcut Landslide and Introduced Landslide Debris Rating Map (from Howes 1985).

TABLE 1. Description of the terrain classes from the Norrish-Cascade study

	MATERIAL ATTRIBUTES					SLOPE ATTRIBUTES		OTHER
TERRAIN CLASS	Type (Landform)	Drainage	% Cover	Depth[a]	Probable Underlying Material	Angle (In Degrees)	Configuration	Gully Erosion Present[b]
1	colluvial mantles with rock outcrops	moderate to rapid	60-20	s	rock	>30	uniform	N
2	colluvial mantle	rapid	100-80	s	rock	≥35	uniform	N
3	colluvial mantle	rapid	100-80	s	rock	≥36	uniform	Y
4	constructional till landforms (rolling till plains)	moderate to rapid	100	d	unknown	<26	uniform	N
5	escarpments of fluvial, fluvioglacial, and till	rapid to moderate	100	d	till or silt	≥33	uniform	N
6	active fluvial sediments (floodplain, fan)	moderate to rapid	100	d	unknown	<20	uniform	N
	constructional fluvial deposits (fan, terrace)	rapid to moderate	100	d	unknown	<20	uniform	
	constructional colluvial deposits (fan)	rapid to moderate	100	d	unknown	<26	uniform	
7	constructional fluvial	rapid to moderate	100	d	unknown	≥20- <33	uniform	N
8	till mantle	rapid to moderate	100	d-s	rock	<26	uniform	N
	mantles of till and colluvium or colluvial mantle	rapid to moderate	100	s	rock	<29	uniform	
9	colluvial mantle	rapid	100-80	s	rock	variable	irregular	N
	till mantle	rapid to moderate	100-80	s	rock	variable	irregular	
	mantles of till and colluvium	rapid to moderate	100-80	s	rock	variable	irregular	
	colluvial mantles and bedrock	rapid	60-20	s	rock	variable	irregular	

TABLE 1. Description of the terrain classes from the Norrish-Cascade study (Continued)

TERRAIN CLASS	MATERIAL ATTRIBUTES					SLOPE ATTRIBUTES		OTHER
	Type (Landform)	Drainage	% Cover	Depth[a]	Probable Underlying Material	Angle (In Degrees)	Configuration	Gully Erosion Present[b]
10	Marine deposits (terrace)	moderate to poor	100	d	unknown	<26	uniform	
11	till mantle	rapid to moderate	100-80	s-d	rock	≥26- <33	uniform	N
	colluvial mantle	rapid	100-80	s	rock	>29- <36	uniform	
	mantles of till and colluvium	rapid to moderate	100-80	s	rock	≥29- <33	uniform	
12	till mantle	rapid to moderate	100-80	s-d	rock	≥26- <33	uniform	Y
	colluvial mantle	rapid	100-80	s	rock	>29- <36	uniform	
	mantles of till and colluvium	rapid to moderate	100-80	s	rock	≥29- <33	uniform	
13	fluvioglacial or colluvial sediments overlying till	rapid to moderate	100	d	till	<33	uniform	N
14	till mantle	rapid to moderate	100-80	s	rock	≥33	uniform	N
	till and colluvial mantle	rapid to moderate	100-80	s	rock	≥33	uniform	
15	till mantle	rapid to moderate	100-80	s	rock	≥33	uniform	Y
	till and colluvial mantles	rapid to moderate	100-80	s	rock	≥33	uniform	

[a] d = >1.5 m, s = <1.5 m.

[b] Y = gully erosion present, N = no gully erosion.

TABLE 2. Class data and statistics for the four terrain classifications

		Original Terrain Classification for Norrish-Cascade Study																
	CLASS*	NP	NPC	NPN	NPCF	NPNF	NCF	NNF	AC	AN	A	PCF	PNF	RFAC	RFAN	RPCN	RACN	SC
1	COLLROCK	35	12	34	0	7		20	82	428	464	0.000	0.206		0.047	0.00		2
2	COLSTEEP	70	40	65	7	20	17	51	299	747	855	0.175	0.308	0.057	0.068	0.57	0.83	3
3	COLSTEPV	35	20	32	10	13	20	34	177	543	641	0.500	0.406	0.113	0.063	1.23	1.80	4
4	DEEPTILL	50	39	31	3	0	5	0	630	523	979	0.077	0.000	0.008	0.000			1
5	ESCARP	50	42	31	19	11	41	14	352	285	495	0.452	0.355	0.116	0.049	1.27	2.37	4
6	FLACT	123	84	75	1	0	1	0	893	803	1516	0.012	0.000	0.001	0.000			1
7	FLUMOD	22	13	14	3	0	5	0	101	132	216	0.231	0.000	0.050	0.000			2
8	GENTMANT	98	76	78	9	4	10	8	903	1183	1707	0.118	0.051	0.011	0.007	2.31	1.64	2
9	IRREG	164	89	150	4	3	5	3	1255	3087	3423	0.045	0.020	0.004	0.001	2.25	4.10	1
10	MARINE	3	0	3	0	0		0	0	69	68		0.000		0.000			1
11	MODMANTL	139	78	131	19	16	34	22	870	1973	2345	0.244	0.122	0.039	0.011	1.99	3.50	2
12	MODMANV	53	36	44	14	11	60	30	674	809	1214	0.389	0.250	0.089	0.037	1.56	2.40	3
13	OVERTILL	18	15	10	0	0	0	0	338	207	467	0.000	0.000	0.000	0.000			1
14	STEEPMAN	57	32	51	14	18	26	30	275	603	720	0.438	0.353	0.095	0.050	1.24	1.90	3
15	STEPMANV	16	12	16	7	5	39	13	187	412	484	0.583	0.313	0.209	0.032	1.87	6.61	4

*from TABLE 1

	Terrain Classification Derived from Vancouver Island Study															
CLASS	NP	NPC	NP	NPCF	NPNF	NCF	NNF	AC	AN	A	PCF	PN	RFAC	RFAN	RPCN	RACN	SC
0	176	120	116	2	0	3	0	1993	2503	3757	0.017	0.000	0.002	0.000			1
1	127	88	108	40	33	135	83	1219	1961	2657	0.455	0.306	0.111	0.042	1.49	2.62	4
2	107	61	96	2	3	2	3	649	1424	1708	0.033	0.031	0.003	0.002	1.05	1.46	1
3	191	140	147	18	9	26	12	1660	2314	3205	0.129	0.061	0.016	0.005	2.10	3.02	2
4	93	47	84	12	11	18	14	394	1061	1272	0.255	0.131	0.046	0.013	1.95	3.46	2
5	210	122	185	36	48	79	102	1054	2129	2557	0.295	0.259	0.075	0.048	1.14	1.56	3
6	29	10	29	0	4		11	67	412	439	0.000	0.138		0.027	0.00		1

TABLE 2. (Continued) Class data and statistics for the four terrain classifications

Terrain Classification Based on Slope Angle, Irregularity, Gullies and Rock
(Potentially Derived from Digital Topography and Remote Sensing)

CLASS	NP	NPC	NPN	NPCF	NPNF	NCF	NNF	AC	AN	A	PCF	PNF	RFAC	RFAN	RPCN	RACN	SC
0	176	120	116	2	0	3	0	1993	2503	3757	0.017	0.000	0.002	0.000			1
1	28	9	28	0	4		11	59	391	418	0.000	0.143		0.028	0.00		1
2	127	88	108	40	33	135	83	1219	1961	2657	0.455	0.306	0.111	0.042	1.49	2.62	4
3	107	61	96	2	3	2	3	649	1424	1708	0.033	0.031	0.003	0.002	1.05	1.46	1
4	175	127	130	16	5	21	8	1446	1830	2642	0.126	0.038	0.015	0.004	3.28	3.32	2
5	111	66	101	10	10	22	15	742	1598	1908	0.152	0.099	0.030	0.009	1.53	3.16	2
6	59	30	55	15	12	22	15	289	774	914	0.500	0.218	0.076	0.019	2.29	3.93	3
7	109	65	94	17	25	41	46	466	940	1141	0.262	0.266	0.088	0.049	0.98	1.80	3
8	41	22	37	8	16	17	44	173	383	450	0.364	0.432	0.098	0.115	0.84	0.86	3

Terrain Classification Based on Slope Angle
(Potentially Derived from Digital Topography)

CLASS	NP	NPC	NPN	NPCF	NPNF	NCF	NNF	AC	AN	A	PCF	PNF	RFAC	RFAN	RPCN	RACN	SC
0	176	120	116	2	0	3	0	1993	2503	3757	0.017	0.000	0.002	0.000			1
1	143	97	113	9	3	12	6	977	1660	2094	0.093	0.027	0.012	0.004	3.49	3.40	2
2	100	70	77	11	3	24	3	1036	1053	1772	0.157	0.039	0.023	0.003	4.03	8.13	2
3	194	118	173	24	19	72	32	1530	2862	3571	0.203	0.110	0.047	0.011	1.85	4.21	2
4	85	48	77	19	20	29	35	465	1113	1342	0.396	0.260	0.062	0.031	1.52	1.98	3
5	169	99	149	31	40	95	81	743	1795	2108	0.313	0.268	0.128	0.045	1.17	2.83	4
6	66	36	60	14	23	28	68	292	818	950	0.389	0.383	0.096	0.083	1.01	1.15	3

Highlights of the analysis of the landslide frequency rates from the Norrish-Cascade case study are as follows (for further details, see Howes, in prep.[4]):

1. Terrain with the highest clearcut landslide rate includes thin mantles of till and/or colluvium on steep, uniform slopes dissected by gullies and escarpments of unconsolidated sediments.
2. Clearcut landslide frequencies increase as slope angle increases on uniform slopes made up of till or colluvial mantles.
3. The clearcut landslide rate is 2.0 times the natural rate; however, the rate varies from 0.8 to 6.6 times for individual terrain classes. The greatest increase occurred on till mantles dissected by gullies, and till and fluvial deposits on moderate slopes.

Note that the clearcut stability rating for terrain class 1 (Table 2) was based on its natural landslide frequency rate because no clearcut landslides occurred in this type of terrain, presumably due in part to the low percentage of area clearcut (18%) and the young age of the clearcuts. The lower than expected clearcut slide rate on steeply sloping colluvial mantles (class 2, Table 2) is also thought to result from these factors.

The Norrish-Cascade Clearcut Landslide and Introduced Landslide Debris Rating Map consists of terrain polygons plotted onto a 1:20 000 scale topographic base map (Fig. 1) (Howes 1985). Each polygon contains a label consisting of two to four symbols: (1) an asterisk if one or more natural failures has occurred within the terrain unit; (2) the clearcut landslide or rapid mass movement stability class number; (3) a plus sign if moderate rates of clearcut slumps are expected (not discussed in this paper but determined in a similar manner as the rapid mass movement rates); (4) a subjective rating (high, moderate, or low) as to the likelihood of landslide debris (originating from a clearcut landslide within the unit) affecting the stream system. Copies of this map are available through Maps B.C. (533 Superior Street, Victoria, B.C. V8T 1X5).

Note that both the terrain class and stability class definitions are made without reference to the presence or number of natural slides in contrast to previous studies. This allowed for the calculation and comparison of meaningful class statistics for natural as well as logging-related failure rates. There are three reasons why ignoring the statistical relationship between the occurrence of natural and clearcut related slides should not be viewed as a class definition limitation: (1) the map polygon label indicates the presence of natural slides; (2) the classes are sufficiently well defined to determine failure prone areas; and (3) there are instances where the relationship is weak.

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[4] Ibid.

5 COMPARISONS TO LESS DETAILED TERRAIN CLASSIFICATIONS

Three other terrain classifications were tested to evaluate the accuracy of identifying potential landslide areas when less complete data bases are available (Table 3). The first is identical to that used in the Vancouver Island study (Sondheim and Rollerson 1985), with the exception that the presence of natural slides is not a class criterion. The definitions of the seven classes are based on dominant material, slope angle, the presence of gullies, and the presence of irregular slope configurations. The second classification, is new and has nine classes. It is defined on a similar basis to the Vancouver Island study, with the major difference being that only the presence of rock is considered in the material category. It is assumed that analysis of Thematic Mapper satellite imagery coupled with digital topography (1:20 000 specifications) could produce a land classification very much like this one. The third classification is based entirely on slope angle. Its seven classes could potentially be derived from digital topography alone.

From one perspective, all four terrain classifications can be considered as four equally valid methods of dividing the landscape. Another viewpoint, however, is that the original Norrish-Cascade classification is the most homogeneous within each class in terms of both geomorphic form and process, and, consequently, it is the most ideal. In fact, for the purposes of this discussion, its associated stability ratings might be regarded as the "true" values for the polygons. Thus, the other classifications are of interest to the extent to which they provide similar stability ratings.

Tabular comparisons are presented (Table 4) of the stability ratings based on the original Norrish-Cascade terrain classification to those associated with the three simpler terrain classifications. Each table is constructed with the original Norrish-Cascade stability class ratings listed along the top and the new stability ratings (as related to one of the new terrain classifications) listed along the left side. Each cell (or position) of the table contains the number of polygons having the corresponding original Norrish-Cascade and new stability class ratings. Because there are four stability classes, the table is of size 4 by 4. This table can be reduced to size 2 by 2 by combining classes 1 and 2 and 3 and 4. The resulting two-class stability classification divides the polygons then into two groups, one rated as stable and the other as unstable. It may be argued that, for very simple planning purposes, the two classes are sufficient. With either table the statistic "p" can be defined as the sum of the main diagonal divided by the total number of observations; "p" indicates the proportion of the observations which are rated identically by the two classifications (see Sondheim and Rollerson 1985, for a discussion of p, its confidence limits, and other related statistics).

In addition to the "p" statistic, two other concepts of interest are the "user accuracy" and the "producer accuracy" (Storey and Congalton 1986). If a certain number of polygons (or hectares) on a map are rated as belonging to a certain class, a user of the map may wonder what percentage of those polygons really are members of that class. Look at the four classes of the original Norrish-Cascade classification compared to that derived from the Vancouver Island classification. It can be seen that 312 polygons (285 + 25 + 1 + 1) are rated as class 1 by the Vancouver Island classification; only 285 of these polygons, or 91%, should be rated as class 1 (in the sense of agreement with the original Norrish-Cascade classification). This 91% is termed the user accuracy for class 1. It is clear that 360 polygons (285 + 60 + 8 + 7) should be rated as class 1 (again considering the original as "true"), but that only 285 of these polygons, or 79%, were rated "correctly". This so-called producer accuracy percentage for class 1 is likely of more interest to the person who produced the map than to someone attempting to use it.

It is significant that, for all six comparisons (Table 4), the user accuracy is progressively worse as one moves from the most stable to the least stable classes. For example, examine the four class comparisons of the original Norrish-Cascade with the classification based on slope angle alone. The four user accuracy percentages range from 95% for class 1 to 34% for class 4. Consequently, it appears that the polygons rated as most unstable are also likely to be the most poorly mapped using one of the simpler classifications. (Note that it does not necessarily follow that the polygons which are "truly" unstable are the most poorly rated. This issue centres on the producer accuracies; it can be seen that they do not always fall into a set pattern.)

TABLE 3. Class definitions for three alternate classifications

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Terrain Classification Derived from Vancouver Island Study

Class 0: slope angle <20°;

Class 1: slope angle >25°,
gullies present,
not dominated by rock*;

Class 2: not class 0 or 1,
slope angle <41°,
not dominated by rock*,
slope configuration is irregular;

Class 3: not in above classes,
slope angle <31°,
dominant material is morainal, fluvial, or fluvialglacial;

Class 4: not in above classes,
slope angle <36°, dominant material is colluvium;

Class 5: not in above classes,
slope angle >30° and dominant material is fluvial or fluvialglacial, or
slope angle >35° and dominant material is colluvium;

Class 6: not in above classes (mostly dominated by rock).

Terrain Classification Based on Slope Angle, Slope Irregularity, Presence of Gullies, and Presence of Rock

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Class 0: slope angle <20°;

Class 1: not class 0, dominated by rock*;

Class 2: not class 0 or 1, slope angle >25°, gullies present;

Class 3: not in above classes, slope configuration is irregular;

Class 4: not in above classes, slope angle <28°;

Class 5: not in above classes, slope angle <33°;

Class 6: not in above classes, slope angle <36°;

Class 7: not in above classes, slope angle< 40°;

Class 8: not in above classes, slope angle ≥40°.

Terrain Classification Based on Slope Angle Alone

Class 0: slope angle <20°;

Class 1: 20° ≤ slope angle < 24°;

Class 2: 24° ≤ slope angle <28°;

Class 3: 28° ≤ slope angle <33°;

Class 4: 33° ≤ slope angle <36°;

Class 5: 36° ≤ slope angle <40°;

Class 6: slope angle ≥ 40°.

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* 'dominated by rock' means one of two things as used here:

(i) rock is the first material listed in the polygon, with no other material overlying it, (e.g., R/...), or

(ii) two conditions hold: rock overlain by a veneer of another material is listed as the dominant material, and as well, rock is listed as the second dominant material, with no other material overlying it,
(Cv)
(e.g., – / R ...) .
(R)

TABLE 4. Comparison of stability classes derived from original terrain classification to those derived from three other terrain classifications

Stability Class Based On	Stability Classes Derived From Original Terrain Classification									
	Class	1	2	3	4	User Accuracy	Class	1 + 2	3 + 4	User Accuracy
Vancouver Island Terrain Classification	1	285	25	1	1	91%	1 + 2	578	18	97%
	2	60	208	11	5	73%				
	3	8	57	115	30	55%	3 + 4	74	262	78%
	4	7	3	52	65	51%				
	[a]Prod Acc.	79%	71%	64%	64%	Diagonal Freq. 673 of 933 (72%)	[a]Prod Acc.	89%	94%	Diagonal Freq. 840 of 933 P = 90%
Terrain Classification Based on Slope Angle, Irregularity, Gullies and Rock	1	285	25	0	1	92%	1 + 2	589	8	99%
	2	59	220	1	6	77%				
	3	9	45	126	29	60%	3 + 4	64	272	81%
	4	7	3	52	65	51%				
	[a]Prod Acc.	79%	75%	70%	64%	Diagonal Freq 696 of 933 (75%)	[a]Prod Acc.	90%	97%	Diagonal Freq. 861 of 933 P = 92%
Terrain Classification Based on Slope Angle	1	167	8	0	1	95%	1 + 2	558	55	91%
	2	161	222	46	8	51%				
	3	10	49	58	34	38%	3 + 4	95	225	70%
	4	22	14	75	58	34%				
	[a]Prod Acc.	46%	75%	32%	57%	Diagonal Freq 505 of 933 (54%)	[a]Prod Acc.	85%	80%	Diagonal Freq. 783 of 933 P = 84%

See text for a description of the table

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[a] Producer Accuracy

Another point of interest on Table 4 is the marked increase in agreement, and the resulting high value, generated from the collapse of the four classes into two. This holds true for both the user and producer accuracies as well as the "p" statistics. The largest increase in accuracy is for the "p" statistic derived from the comparison between the original Norrish-Cascade and the slope-only classifications. With four classes, it is 54%, increasing by 30 percentage points to 84%, with two classes. The user accuracies for the less stable classes have changed from 38% (class 3) and 34% (class 4) to 70% (class 3 plus 4). The most impressive comparisons, however, involve the original classification to that based on slope angle, irregularity, gullies, and rock. Here, the two values for "p" are 75% (four classes) and 92% (two classes). The user and producer accuracies for class 3 plus 4 are 81% and 97%, respectively. Nearly as high results are obtained with the comparisons of the original Norrish-Cascade and the Vancouver Island classifications. Such comparisons suggest that, particularly for the two-class stability rating system, the simpler classifications may be nearly as useful as the original Norrish-Cascade. Also suggested is the notion that a classification derived in one area may be applied with reasonable results to another geomorphically similar area.

6 AN EXAMINATION OF THE TERRAIN CLASS STATISTICS

The class statistics (Table 2) for the terrain classifications are quite instructive. Because of space limitations, only the more interesting aspects are discussed. For the original Norrish-Cascade classification, the probability of clearcut failures occurring within a polygon (PCF) varies from 0.0 to approximately 0.6. The probability of natural failure (PNF) ranges from 0.0 to 0.4. The ratio of these probabilities (RPCN) ranges from 0.0 and 0.6 to 2.3. Values greater than 1.0 imply that the likelihood of one or more clearcut failures occurring is greater than the likelihood of one or more natural failures occurring. From the RPCN values for the slope angle only terrain classification, it can be inferred that slopes >24° and <28° (class 2) are four times more likely to develop clearcut-related failures compared to natural failures (for the type of terrain represented in this study).

A series of relationships are plotted as scatter graphs in Figure 2. The first row (graphs 1, 2, and 3) shows the probability of the occurrence of clearcut-induced slides (PCF) graphed against the ratio of clearcut slides to clearcut hectares (RFAC). The values for the classes of the original Norrish-Cascade terrain classification show a generally strong, positive, somewhat non-linear relationship. For the classification based on slope angle, slope irregularity, gullies and rock, the relationship can be similarly described, although the shape of the curve is different. The same can also be said regarding the slope-only classification. Thus the specific characteristics of the relationship appear to be classification-dependent. Nevertheless, where area data may not be available, use of PCF instead of RFAC to define stability ratings seems well justified (Rollerson *et al.* 1986).

The relationship of the ratio of clearcut to natural failure rates on a per-hectare basis (RACN) to the stability rating (SC) is shown in graphs 4, 5, and 6. In all three cases there are no trends. The maximum RACN values are 6.6, 3.9, and 8.1, corresponding to stability ratings of 4, 3, and 2, respectively. Even within any stability class as related to any of the terrain classifications, RACN may vary considerably. For stability class 4, the three values for RACN are 1.8, 2.4, and 6.6 for the original Norrish-Cascade classification. Thus, the relative increase in the likelihood of failure cannot be judged from the stability rating (or the slides per hectare ratio).

Since the presence of natural slides has traditionally been used as a sign of warning related to the potential for clearcut slides, the probability of one or more clearcut failures (PCF) was plotted against the natural failure probability (PNF) in graphs 7, 8, and 9. In all three cases there is a positive relationship. Only for the last classification do the points appear to be well behaved. Nevertheless, the use of natural failure as an indication of susceptibility of clearcut-induced failure seems valid. As before, the results point to the degree to which the interpretation of various relationships may be influenced by the classification used in defining those relationships.

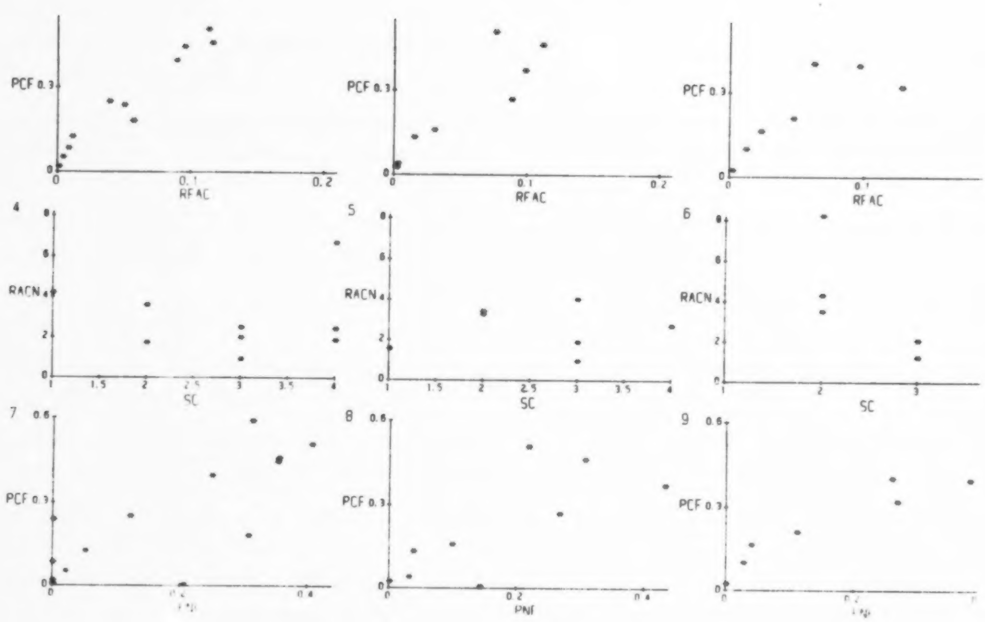

FIGURE 2. Scatter graphs of various statistics from the different classifications; data from Norrish-Cascade terrain classification (graphs 1, 4 and 7); data from the terrain classification based on slope angle, configuration, the presence of gullies and rock (graphs 2, 5 and 8); and data from the terrain classification based on slope angle (graphs 3, 6 and 9).

7 CONCLUDING REMARKS

The described terrain evaluation method provides an objective way of estimating the likelihood and potential rate of failure associated with clearcutting. Equally important in the long term, it may provide regional levels of planning a means of developing acceptable estimates from digital data sources, namely digital topography and space imagery from the Thematic Mapper and Spot satellites. Work directed at assessing such data directly for stability mapping should be encouraged. Other areas which should be investigated include better methods of estimating the size and volume of landslides and of determining the route a slide is likely to follow. Particularly valuable would be a quantitative method of establishing whether or not a potential slide will reach the stream network and, if it does, calculating both the point and length of stream affected.

8 ACKNOWLEDGEMENTS

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SESSION 3 PREDICTION/CONTROL

CONSIDERATION OF SOIL PRODUCTIVITY DURING FOREST MANAGEMENT ACTIVITIES: THE USDA FOREST SERVICE APPROACH IN THE PACIFIC NORTHWEST

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ABSTRACT

Consideration of forest soil productivity maintenance and improvement is an important component of planning silvicultural activities on lands managed by the USDA Forest Service in the Pacific Northwest. As a public land management agency, the Forest Service is legally mandated to maintain or enhance long-term productivity of lands under its management while, at the same time, supporting increased utilization of forest resources, provided other resource values are not adversely affected. This paper describes the direction and processes followed by Forest Service land managers to ensure that soil productivity is not degraded to unacceptable levels by forest management activities. Included are discussions of legal and agency direction concerning soil productivity protection, the risk assessment process, management prescription development, contractual considerations, and monitoring and assessment of management activities.

1 INTRODUCTION

As an agency, the USDA Forest Service supports increased utilization of our forest resources, provided that other resource values are not adversely affected. We are also legally mandated to maintain or enhance long-term biological productivity of forest lands under our management. To some, these goals may seem contradictory. We believe, however, it is possible to achieve the first goal and meet the environmental constraints imposed by the second.

The harvest and removal of forest products, and subsequent land treatment operations such as slash disposal and site preparation, generally result in some degree of soil disturbance. Soil disturbance is not necessarily harmful, and in fact, may often be a management objective, particularly where site preparation and tillage are concerned. However, as land managers, we are concerned when soils are disturbed to the point where their inherent capability to produce biomass, whether it be in the form of cubic meters of timber, forage for livestock and wildlife, or fuel for energy production, is reduced to unacceptable levels.

This type of detrimental soil disturbance, or soil damage, most often is in the form of compaction, puddling, and displacement caused by the use of ground-based harvesting and slash disposal equipment. It can also take the form of charred soils in intensely burned areas.

The processes involved in these various forms of soil resource damage and their subsequent effects on forest tree growth have been well researched. An excellent review of the literature has been prepared by Alexander and Poff (1985). This paper will not dwell in detail on the findings of such studies other than to say that the majority have found that most forms of soil damage negatively influence tree growth. Much of the research that has been completed has been on an individual tree basis. Problems have arisen on an operational scale in determining threshold levels for, or defining when, soil damage exists and in determining how much damage can be tolerated on a given area of land before unacceptable stand growth losses occur.

2 DIRECTION/STANDARDS

In light of our legal mandate and realizing the necessity for some type of direction to meet the intent of those laws, land managers within the Pacific Northwest Region of the USDA Forest Service (Oregon and Washington) developed a policy dealing with soil productivity protection in June, 1979. This policy was subsequently revised in September, 1983. Specific objectives of this policy are as follows:

1) to plan and conduct land management activities so that reductions of soil productivity potential caused by detrimental compaction, displacement, puddling, and severe burning are minimized; nutrient capital on forest and rangelands is to be maintained at acceptable levels;
2) to plan and conduct land management activities so that soil loss from accelerated surface erosion and mass wasting caused by these activities will not result in an unacceptable reduction in soil productivity and water quality; and
3) to ensure that the Pacific Northwest Region, and all National Forests within it, will have realistic measurable soil protection standards and guidelines which can be monitored and which are in accord with and supportive of land management objectives.

Generally speaking, the magnitude of growth loss on a stand basis is determined largely by the degree, extent, and duration of soil damage effects (Froehlich 1973). Degree refers to the amount of change in a particular soil property, such as porosity, bulk density, or strength, and the depth to which that change occurs. Extent refers to the amount of land surface affected by that change. Duration refers to the length of time the change in a soil property can be expected to affect tree growth and is influenced by factors such as soil type and climate. In some instances, these impacts can last up to several decades (Alexander and Poff 1985).

Based on the best available research results, standards for determining detrimental compaction, puddling, displacement, and severely burned soils were developed. Standards emphasize observable and measurable soil characteristics that field personnel can easily use to monitor activity effectiveness. Generally they focus on characteristics that do not require expensive and time-consuming laboratory procedures to obtain. The standards for puddling, detrimental displacement, and severely burned were developed somewhat arbitrarily. It is often difficult to state quantitatively the changes in specific soil properties that are necessary to reduce productivity to unacceptable levels. It is also difficult to measure such changes. For example, one could define detrimental displacement in terms of nutrients lost from the site, or as we have done, in terms of depth of soil lost beyond which productivity losses are almost certain to occur. An upper limit on the total amount of soil damage to be tolerated on an activity area basis was also established. These standards are as follows:

1) detrimental compaction
    a) volcanic ash and pumice soils - an increase in soil bulk density of 20% or more over the undisturbed level;
    b) all other soils - an increase in soil bulk density of 15% or more over the undisturbed level, and/or a macropore space reduction of 50% or more, and/or a reduction below the 15% level as measured by an air permeameter.

    (A different criterion for detrimental compaction was established for volcanic ash and pumice soils because of their unique physical properties and management requirements.)

2) puddling

Soil puddling is a physical change in soil properties due to shearing forces that destroy soil structure and reduce porosity. Detrimental puddling can be observed as vehicle tracks when soil is molded and when depth of rutting reaches 6 inches (15 cm) or more.

3) detrimental displacement

Detrimental displacement is the removal of more than 50% of the topsoil or humus-enriched A1 and/or AC horizons from an area of 100 ft2 (10 m2) or more which is at least 5 ft (1.5 m) in width.

4) severely burned

Soils are considered severely burned when the top layer of mineral soil has been significantly changed in color,usually to red, and the next 0.5 inches (1.25 cm) blackened from charring by heat conducted through the top layer.

5) areal extent of soil damage

The total acreage of all detrimental soil conditions following management activities should not exceed 20% of the area to which those activities are applied. Detrimental soil conditions can often occupy from as little as 10% to as much as 60% of an activity area. Generally, 3-5% of an activity area is committed to main and secondary roads and to landings.

It was not intended to develop absolute numerical values of acceptable levels of disturbance that are appropriate for every unique set of soil conditions found in the Region. The values presented here as limits of acceptability are intended to broad Regional standards. Land managers usually do not want to exceed the standards by significant amounts and may, in fact, want to strive for higher standards. Those forest managers that choose to accept levels of disturbance less than the limits of acceptablity are encouraged to do so provided they complete an economic evaluation of their proposal.

3 RISK ASSESSMENT

Prior to the implementation of any management activity on National Forest System lands, an environmental assessment by an Interdisciplinary (ID) Team is completed. During this process, the potential of soils within the project area for compaction, puddling, displacement, and damage by severe burning is evaluated. Depending on the nature and location of the proposed project, a Forest Soil Scientist may be asked to either serve as an ID Team member or provide input to the Team so that the best possible management alternative can be developed. Degree of soils input can vary from providing and/or interpreting existing soil survey information to conducting detailed on-site investigations. Recommendations are generally based on individual knowledge of soil science and forest management practices as well as past experiences under similar conditions.

Reconnaissance level (1:70 000 scale) soil survey information is available on all National Forests within the Region. Timber sale planners use this information to determine where potential soil related problems may exist and to determine the need for soil scientist input. Several National Forests are in the process of collecting more detailed soil survey information.

4 PRESCRIPTION DEVELOPMENT

Based on the results of such investigations, specific soil management objectives cannot be overemphasized. Objectives provide the basis for prescription development and any follow-up monitoring that may be required. They must be stated in terms of quantifiable results to be achieved within specified timeframes if they are to be developed into meaningful contract language. Simply stating that a certain percentage of soil damage is acceptable on an activity area is, in most cases, not enough. For example, desired skid trail spacing should be specified; or, if yarding off designated skid trails is to be allowed, soil conditions beyond which operations should cease must be described. Time of year when optimum soil conditions can be expected should also be outlined. For prescribed burning and/or tillage-site preparation projects, end results and conditions necessary for obtaining them must be described in detail. If a successful project is to be completed, both the operator and the timber sale administrator need to know exactly what is expected.

The development of soil management prescriptions focuses on either avoidance or mitigation of soil damage. Generally it has been our experience that it is more effective and less costly to avoid soil damage initially rather than to repair it after the fact.

The Pacific Northwest Region has taken several approaches to accomplish the objectives of limiting the degree and extent of soil damage and keeping it within Regional standards. One of the most commonly used methods has been to limit timber harvest activities to those periods of the year when soil damage is least likely to occur. For compaction, this generally has been during winter, over snow or frozen ground, or during the driest parts of the year when soils are least susceptible. Specific soil moisture percentages have also been proposed for individual soils above which operations off designated skid trails would not be allowed and which can be included in timber sale contracts. These percentages are used primarily where machine slash piling operations are planned.

The Region has also explored the use of "end result" contracts in which the desired results are specified and operators are allowed to use any available harvesting techniques to meet them. If objectives are not met, operators are liable for any restoration work required.

Another approach has been to specify the use of low ground pressure yarding equipment on soils particularly sensitive to compaction damage. This has been successful in some cases although it is still possible to incur unacceptable amounts of soil damage with this type of equipment when not properly operated.

When ground skidding is the preferred method of logging, the surface soil condition classes described in the Regional direction can most easily be met with the fewest stand entries by using designated skid trails, felling to lead, winching of logs, and broadcast burning of fuels. When such methods are used, there may not be much added advantage of using low ground pressure equipment to achieve soil productivity protection objectives. Designated skid trails are a common practice in the Region and even where compaction has occurred from previous entries, minimal new compaction occurs when old skid trails are used.

Duration of soil damage effects can be minimized through some sort of amelioration such as soil tillage or fertilization. The Region has had a great deal of success in the use of specially designed tillage equipment to minimize the effects of soil compaction. Fertilization generally has not been used on a large scale to ameliorate the effects of topsoil loss resulting from displacement or surface erosion.

5 MONITORING

After the standards had been developed and adopted for use, a system of monitoring was needed to ensure that, in fact, we were meeting our soil productivity protection objectives. At first, there was no standard sampling procedure available and each of the 19 National Forests within the Region developed its own procedures. This led to inconsistencies in sampling between National Forests and, often, indefensible results. Results of sampling were frequently challenged by individuals within the agency as well as from outside.

In 1981, a standard sampling system was developed in order to obtain a statistically sound sample. This was later revised in 1983 (Howes *et al.* 1983). Objectives of the sampling system are:

1) to obtain a representative sample;
2) to control level of precision;
3) to obtain consistent results with repeated sampling; and
4) to sample all soil characteristics of interest at one time.

Computer programs have also been developed to assist in analysis of field data (Starr and Geist 1983; Hazard *et al.* 1985).

Forest soil scientists have been using the sampling procedure for several years now to obtain sound, defensible information on the impacts of management activities on forest soils. One example of such a monitoring project will be discussed elsewhere in these proceedings (see Laing). In cases where management objectives have not been met, prescriptions have been modified and/or mitigative measures prescribed.

A monitoring project is not conducted on every unit of every timber sale in the Region. Units are selected based on management's need for information on specific sets of activities applied to extensive or important soil types. The ability to extrapolate information to other areas has been a prime consideration in selecting units for detailed monitoring. Now that a level of credibility in our monitoring has been established, fewer quantitative sampling procedures are now being employed.

6 RESULTS

Generally speaking, the criterion of 20% maximum allowable soil damage on activity areas can be achieved using state-of-the-art management techniques such as designated or pre-approved skid trails, reduced slash clean-up or prescribed burning, and low ground pressure yarding equipment. Problems arise, however, in stands that have been entered previously or in partial cut situations where the standards may already be exceeded. In these situations, soil damage should be mitigated upon final removal.

The Pacific Northwest Region of the Forest Service believes strongly that the policy and standards developed for protection and enhancement of long-term soil productivity are reasonable and prudent. There are no plans to revise them at this time; however, should more information become available through research and continued monitoring, they will be modified as appropriate.

7 SUMMARY

Current, state-of-the-art forest management practices generally can be applied to various stand conditions and meet the intent of the soil productivity protection policy without incurring excessive costs. It appears the issuance of the policy and standards for soil resource protection has been a major factor in encouraging practices that maintain or improve both short- and long-term site productivity. The soil productivity standards appear reasonable and appropriate based on current knowledge of factors affecting soil productivity and site quality.

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SESSION 3 PREDICTION/CONTROL

DETRIMENTAL SOIL COMPACTION RESULTING FROM A FELLER BUNCHER AND RUBBER-TIRED SKIDDER TIMBER HARVEST OPERATION: A CASE STUDY

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ABSTRACT

A monitoring project was conducted in 1983 on a timber sale unit on the Colville National Forest (1) to quantify the degree and extent of detrimental soil disturbance following clearcut, whole tree harvest with a feller buncher and conventional rubber-tired skidder; and (2) to determine if USDA Forest Service, Pacific Northwest Region, soil management direction had been met. Statistical analysis and interpretation of data, study conclusions, management recommendations, and a discussion of site productivity and economic implications are presented. Results of a soil restoration demonstration project on the unit are also described.

Soil disturbance assumed to be detrimental to plant growth was measured on 41.8% (±10.8%) of the unit. Most of this disturbance (98%) was detrimental compaction indicated by a bulk density increase of 20% or more over the pre-activity level at a soil depth of 10-15 cm. The mean bulk density increase of the detrimentally compacted sample points was 36%. Pacific Northwest Regional direction, that a minimum of 80% of an activity area be left in a condition of acceptable productivity potential for trees and other managed vegetation following land management activities, had not been satisfied in this instance.

1 INTRODUCTION

Soil productivity loss resulting from an efficient but potentially soil-damaging yarding method is a management concern on the Colville National Forest in Northeastern Washington. Unit 1 of the Best Shot Timber Sale on the Newport Ranger District was monitored to assess soil compaction following clearcut, whole tree timber harvest with a feller buncher and conventional rubber-tired skidders. The District Ranger and others believed the unit to be excessively compacted and in conflict with Regional direction (USDA Forest Service Manual 2520.2-4. Region 6 Supplement 45. Sept. 1983). Quantitative data were needed to determine degree and extent of detrimental compaction.

Most of Unit 1 occurs on a nearly flat glacial outwash terrace. Soils are characterized by Orwig sandy loam, 0-20% slopes, in the Soil Survey of the Pend Oreille Area, Washington (Donaldson *et al.* 1985). The Orwig soil series is classified as sandy, mixed, frigid Typic Xerocrepts. Although the soil was not classified in an Andic subgroup, the surface did have volcanic ash influence as evidenced by the relatively low pre-activity bulk density. Timber sale administration records show soils were moist at the time of logging in late spring of 1983, suggesting they were at or near field capacity. Vegetation has been classified as the Cedar-Pachistima habitat type (Williams and Lillibridge 1985). The stand was dominated by lodgepole pine and volume removed averaged 65 m^3ha^{-1}.

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2 PROCEDURES

Sampling procedures and statistical methods used are described in *Guidelines for Sampling Some Physical Conditions of Surface Soils* (Howes *et al.* 1983). Soil conditions were categorized to the nearest 0.3 m (1 ft) along eight systematically located, randomly oriented 30.5-m (100-ft) transects. Adjacent haul roads were not included in the sample. Soil condition classes were based on definitions established by the Forest Service, Pacific Northwest Regional Office (USDA Forest Service Manual 2520.2-4. Region 6 Supplement 45. Sept. 1983). Soil cores of approximately 45 cm^3 in volume were collected at 3-m (10-ft) intervals at a depth of 10-15 cm (4-6 inches). Random cluster core samples were collected in an adjacent undisturbed stand with similar soils and topography. Sampling was designed to produce estimates within ± 20% of the true mean at the 0.1 probability level. A subjective assessment of soil resistance to tile spade penetration and of the presence of induced soil platiness was also recorded at the sample points.

Core samples were collected at 3-m (10-ft) intervals along nine random 30.5-m transects as well, to assess effectiveness of a soil rehabilitation demonstration project on the site.

3 RESULTS

Soil damage was measured on 41.8% (± 10.8%) of the unit. Most disturbance (98%) was detrimental compaction, indicated by a bulk density increase at a depth of 10-15 cm of more than 20% over pre-activity samples. The mean bulk density increase of the detrimentally compacted sample points was 36%. Regional direction that a minimum of 80% of an activity area be left in a condition of acceptable productivity potential for trees or other managed vegetation following land management activities was not satisfied.

Of the 28 sample points classified as severely compacted according to resistance to shovel penetration and induced soil platiness, 18 were detrimentally compacted in terms of bulk density increase. Eighty-four percent of the detrimentally compacted points were classed as moderately or severely compacted, based on shovel penetration. When sampled, the unit was nearly devoid of slash and debris. The most obvious compaction was associated with the large landings and heavily traveled skid trails. Some soil displacement occurred when a fire line was constructed around the unit (the area was originally scheduled for a prescribed burn). A small, poorly drained area was affected by machinery, such that a small amount of soil puddling and standing water occurred.

During the summer of 1984, Unit 1 was remonitored to assess the effectiveness of a site rehabilitation demonstration project using a small five-tined, subsoiler towed by a D-3 or equivalent-sized crawler tractor. The entire unit was subsoiled using this piece of equipment.

Results indicated some reduction in the areal extent of detrimental compaction at the 10-15 cm depth, but not enough to satisfy the Regional standards for nondetrimentally disturbed soil within an activity area. Specifically, the percent of detrimental soil compaction is within ± 15.8% of the mean of 35.5%, 90% of the time. These results are a slight improvement over the post-treatment mean of 41.8% ± 10.8%. The probability that an error has occurred or that the area has not exceeded the standard is 5%.

The mean bulk density of the detrimentally compacted samples was 33% greater than the mean pre-activity bulk density following the rehabilitation effort, as compared to 36% following timber harvest. The small tillage implement used appears especially promising for site preparation activities where the objective is to achieve mineral soil exposure or to redistribute duff and litter, particularly if the number of stumps and amount of slash remaining on the site is not excessive.

4 DISCUSSION

4.1 Recommendations

Upon review of the timber sale contract and District records, several factors that most likely contributed to excessive amounts of soil compaction became evident. They are:

1) the use of a track-mounted feller buncher which felled and transported trees individually;

2) the unrestricted yarding pattern of the rubber-tired skidders (the flat terrain in most of the unit probably contributed to this problem);

3) the moist condition of the medium-textured upper horizons during operations; and

4) the additional traffic required due to the large number of trees removed (dbh averaged 20 cm while volume averaged 65 m^3ha^{-1} (17 000 fbm ac^{-1}); contract specifications also required removal of trees down to a 10-cm top).

The traffic pattern of the rubber-tired skidders appeared to be an important determinant of the extent of compaction. Placement of log bunches dictated this pattern. Conventional track-mounted feller bunchers can handle only one tree at a time. Placement of reasonably sized log bunches adjacent to well-spaced skid trails was difficult.

Feller bunchers equipped with a hydraulic boom arm are designed to collect bunches and place them where they can be systematically yarded. Skid trail spacing of 15-18 m (50-60 ft) can be achieved with these machines. They have a low center of gravity and are set on wide tracks resulting in low ground pressure. Considering the large number of trees per hectare in Unit 1 (approximately 617-864 trees per hectare), the feller bunchers with the hydraulic boom arm would have been very efficient and lessened the compaction risk. They are recommended, in lieu of the conventional feller bunchers, for treating similar stands on the Newport Ranger District. If conventional feller bunchers are used, it is recommended that units be harvested over snow.

Despite utilization specifications, there was a large amount of unmerchantable material yarded to the landings. More debris, up to 22-34 tonnes ha^{-1} (10-15 tons ac^{-1}), could have been left in the unit to aid nutrient cycling, provide favorable microsites for tree establishment, and reduce the risk of serious soil compaction. Little mineral soil exposure was needed to accommodate planned artificial regeneration (planting).

Moist soil conditions during harvest probably contributed to the soil compaction problem, if it is assumed that fewer equipment passes resulted in detrimental compaction because of the higher moisture content. Skidding and movement of the feller buncher was random, which may have made high soil moisture a very significant factor. Restricting logging to the dry season might probably have reduced compaction, but controlling the method and pattern of yarding may have been the most effective way to control the extent and distribution of compaction in this instance.

The small five-tined subsoiler used on Unit 1 successfully restored abandoned skid trails and roads to a productive state in other areas of the Pacific Northwest Region, but was ineffective in this situation. A more powerful tractor was recommended by the operator in view of the degree and depth of compaction and the large number of stumps. The depth of subsoiling and timing of the operation should be more clearly defined than was the case in this demonstration, to ensure success of future restoration projects.

4.2 Productivity and Economic Implications

How could this soil damage influence future wood production? A potential yield of 96.8 m^3ha^{-1} (25 264 fbm ac^{-1}) is projected over a 60-year rotation. This yield estimate is from the Colville National Forest Yield Tables (Even 1982) for the cedar-hemlock working group and assumes precommercial thinning, commercial thinning at age 40, 35.1 cm (13.8 inch) dbh at final harvest, cutting to an 11.4 cm (4.5 in) top and 17.8 cm (7 inch) dbh specifications. Approximately 17.5 and 79.2 m^3ha^{-1} (4576 and 20 689 fbm ac^{-1}) could potentially be removed during commercial thinning and final harvest, respectively.

Research indicates a volume growth reduction of 69 and 73% on heavily used skid trails (Froehlich 1979; Wert and Thomas 1981, respectively). Froehlich and McNabb (1984) developed a chart showing the relationship between an increase in bulk density and a decrease in seedling growth based on a number of studies. This chart indicates a 36% increase in bulk density could result in a 26% decrease in height growth. A conservative estimate of 35% volume growth reduction over the next rotation is predicted for the detrimentally compacted areas in Unit 1, based on these studies.

The mean areal percentage of detrimental compaction within the unit was 41.8%. Volume loss at final harvest is projected to be 11.6 m^3ha^{-1} (3027 fbm ac^{-1}). Loss during commercial thinning is estimated to be 2.6 m^3ha^{-1} (699 fbm ac^{-1}). This equates to a discounted monetary loss of approximately ($138/ha). Costs are based on estimates by Steblina (1983) of $81/$m^3$ ($125/$10^3$fbm) in 1983 U.S. dollars. Monetary losses projected at final harvest and commercial thinning are 1983 values discounted at a rate of 4% over 60 and 40 years, respectively.

A loss of 195 m^3 (125 664 fbm), or 15% of the total potential yield, is projected due to detrimental soil compaction on this 13.8 ha unit during the next rotation if effective remedial measures are not implemented.

This prediction does not consider the impact of the detrimental compaction on special practices designed to increase yields, such as planting of genetically superior seedlings. Also, the cumulative impact of additional compaction incurred during the commercial thinning is not taken into account.

Assuming that 10% of the unit was detrimentally compacted because of planned skid trails and landings, estimated volume loss at final harvest would be 2.8 m^3ha^{-1} (742 fbm ac^{-1}). Volume loss incurred at commercial thinning is projected to be 0.6 m^3(160 fbm ac^{-1}). This results in discounted monetary loss of approximately $12.

Approximately 46.6 m^3 (30 056 fbm) or 3.5% of the total potential yield of the unit would be lost due to dedication of land to skid trails and landings (versus cable yarding utilizing system roads as landings). However, from a practical standpoint, planned trails and landings may be needed to manage the stand at a level intensive enough to realize maximum potential yield.

5 SUMMARY

The USDA Forest Service is required to ensure a sustained yield of timber and maintain or enhance soil productivity. This should be accomplished in a cost efficient manner. The discounted dollar losses estimated to be due to detrimental compaction give some indication of the cost-efficiency of mitigation practices. Subsoiling the unit is a breakeven investment at best, assuming a cost of $111-222 (US)/ha ($45-90/ac) to accomplish and estimated discounted losses of $136 (US)/ha ($55/ac) due to soil compaction. Prevention of excessive soil compaction by modifying yarding and fuel-treatment practices would have been the most cost-efficient approach in this situation. For example, to yard the unit with crawler tractors and rubber-tired skidders, utilizing incidental winch lines pulling to designated skid trails, may result in no additional costs over the so called "loggers choice". Yarding with tops attached at an additional cost of about $37 (US)/ha ($15/ac) would be a good investment if the landing size were controlled. This accomplishes slash-treatment objectives and avoids the risk of soil compaction problems associated with tractor piling or the need for a prescribed burn fireline.

The assumptions will change in other circumstances, but this analysis shows the land manager the possible economic and productivity implications of monitoring the results of forest management practices that cause soil degradation.

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SESSION 4

Rehabilitation

Session Chairman:
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SESSION 4 REHABILITATION

THE REHABILITATION OF DEGRADED FOREST SOIL IN BRITISH COLUMBIA: AN OVERVIEW

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ABSTRACT

The rehabilitation of degraded forest soil has yet to receive adequate attention in British Columbia. Although activities by the Ministry of Forests and Lands, Research Branch, have yielded positive results in regard to both soil erosion control and the restoration of soil productivity, the implementation of these findings has been slow at best. Lack of policy enforcement for degradation prevention or rehabilitation, antagonistic attitudes within both the public and private forestry sector toward environmental regulation, and minimal funding of operations and/or research are the primary problems. Until these factors are addressed, the current level of soil degradation associated with forest harvesting will continue, as will the negative impacts on the forest resources of the province.

1 INTRODUCTION

Forest soil degradation and subsequent rehabilitation are major forest management problems in British Columbia that have yet to receive adequate attention within the forestry sector. In this paper, forest soil degradation refers to an alteration of soil physical, chemical, and/or biological properties, which adversely affects forest resources. These adverse effects may include loss of site productivity, accelerated soil erosion, reduction in water quality and fishery values, and deterioration of the visual quality of forests. Whether it is large-scale degradation, as associated with ground-based logging, or more isolated erosional problems, the short- and long-term impacts on forest resources can be substantial.

This paper has two principal objectives. The first is to provide a review of policies and attitudes in the forestry sector toward soil degradation and rehabilitation. The attitude of forest managers is an important component of any discussion of forest soil rehabilitation because through proper planning and the adoption of high operational standards, much of soil degradation and its associated problems can be prevented. Preventative management can free manpower and financial resources to deal with the limited degradation that is a natural consequence of forest harvesting activities, and the goals of a rehabilitation program can then be attained. It must also be noted that the perspective presented is a result of the author's 10 years of forest rehabilitation activity throughout the province.

The second objective of this paper is to provide an overview of forest soil rehabilitation activities in British Columbia. These efforts have concentrated on erosion control and on the restoration of forest productivity on severely degraded soils. A review of past programs, the status of current activities, and identification of future needs are presented. References to publications, programs, and supervisory personnel are provided to assist the reader in pursuing details of specific activities. Only major rehabilitation programs are reviewed, although numerous local forest soil rehabilitation programs have been carried out throughout the province.

2 FOREST SOIL DEGRADATION AND REHABILITATION IN BRITISH COLUMBIA: POLICIES AND ATTITUDES

The perception, within the Ministry of Forests and Lands, of the extent of soil degradation has changed considerably in the last five years. For example, a 1983 unpublished survey of all interior British Columbia Forest Regions revealed that the perceived areal extent of cutover lands in the interior regions occupied by skidroads and landings varied from 3% in Kamloops to 20% in the Cariboo. Since that time, the more accepted standard of 20-25% (Froehlich 1973) has been adopted, indicating that a more realistic perception of the extent of soil degradation has prevailed.

Unfortunately, research and operational programs directed at soil degradation and rehabilitation have not fared well over the past few years. It is recognized that poor economic conditions in recent years in both the government and private forestry sectors have played a major role in the decline of programs directed at reducing soil degradation. It is hoped that as the economy improves, more funding will become available for preventative and rehabilitation programs. However, there still exists a strong, antagonistic attitude within both the forest industry and some sectors of the Ministry of Forests and Lands towards environmental restrictions or guidelines aimed at the prevention of soil degradation during logging activities. It is this antagonistic attitude of both foresters and forest managers that poses a major obstacle to the prevention and rehabilitation of forest soil degradation.

The Forest Act (1978) provides the B.C. Ministry of Forests and Lands the mandate to protect and conserve the forest resources and to encourage the attainment of maximum productivity of those resources. To help meet this obligation, the Ministry of Forests and Lands, Silviculture Branch, adopted the Basic Silviculture Policy 009: Reduction of productivity losses from logging operations (1984). This policy not only provides broad forest management goals to reduce soil degradation, but also provides the avenue to penalize operators who cause excessive degradation. Unfortunately, objective definitions and enforceable evaluation criteria pertaining to soil degradation with regard to forest productivity are still lacking. Therefore, little improvement in harvesting methods is likely to result from this policy until such criteria are implemented.

Fortunately, the problem of soil erosion, though mentioned in the Silviculture Policy, is regulated primarily with regard to water quality and fishery values. Without enforcement by Fisheries and Oceans (DFO) or the B.C. Ministry of Environment and Parks, it is doubtful whether many of the limited activities undertaken by the forestry sector over the past few years to control erosion would have occurred. Even with the DFO regulations in effect, some forestry companies and Ministry of Forests and Lands personnel have the strong view that "extra" expenditures not related to timber production are not affordable at this time. However, the shortage of funds for necessary environmental improvement activities within logging operations does not justify the continued use of less expensive logging methods that can cause extensive soil degradation. This is a short-sighted point of view and such a short-term approach could have dire consequences for the practice of forestry in the future.

The following examples illustrate this short-sighted attitude, which is exhibited in the industrial sector in particular. In 1984, DFO put forth new Coast Logging Guidelines to the Ministry of Forests and to the forest companies. Developed by an interdisciplinary team of experts, these guidelines presented fundamental considerations to be included in logging operations for the protection of the fishery resource. These considerations are general, flexible, and allow for site specific modification. At the request of the Council of Forest Industries (COFI), the chief lobbying organization for the forest companies, these guidelines have yet to be adopted by the Ministry of Forests and Lands. The guidelines have been, and still are, the subject of what appears to be an excessively time-consuming review process.

A second example, also involving COFI, pertains to the landing rehabilitation guidelines in the Prince George Forest Region. Seeking to provide for more effective and enforceable landing rehabilitation, the Regional staff rewrote the existing guidelines and adopted a stronger stance toward enforcement of landing rehabilitation requirements. These new guidelines require more extensive soil rehabilitation measures to be undertaken, but reduce the overall number of landings to be treated. After meetings with Regional and District staff where assurances of flexible enforcement and provision of adequate cost allowance in stumpage appraisals were given, COFI still declared an intention to have the guidelines removed by appealing to higher Ministry of Forests and Lands authorities. Such antagonistic attitudes toward environmentally sound constraints to forest harvesting must be resolved if proper forest management, including the maintenance of the productive land base and protection of other forest resources, is to be practiced in British Columbia.

3 FOREST SOIL REHABILITATION ACTIVITIES IN BRITISH COLUMBIA

Proper planning combined with high operational standards can prevent or alleviate much of the soil degradation associated with forest road development and harvesting operations. For soil degradation that is unavoidable, or in some cases not anticipated, the forest manager must have available various soil rehabilitation techniques for immediate implementation. Such techniques can be divided into two broad categories: erosion control and restoration of site productivity. Although the objectives and methodologies applicable to these categories are not always independent of each other, they will be discussed separately for ease of presentation.

3.1 Erosion Control

Historically, erosion control activities in the British Columbia forest environment have focused on the protection of water quality and fish habitat. Reduction of road maintenance costs, enhancement of soil stability, and prevention of site productivity losses have usually been secondary considerations. In 1978, the Research Branch of the Ministry of Forests initiated the first major erosion control program in the British Columbia forestry sector. Implementation of erosion control programs at present by the Ministry of Forests and Lands and by forest companies is still, however, not widespread.

The primary thrust of the Research Branch erosion control program has been bioengineering, the use of live plants as building material for erosion control and landscape restoration (Schiechtl 1980). Initial activities dealt with the control of surface erosion by establishing a grass-legume cover crop. Later in the program, investigation of the propagation and use of native shrub species was undertaken. Most recently, testing of new erosion control revegetation mats (ECRM) has been incorporated into the program. The results from the first two phases have been very positive (Carr 1980; Homoky 1984; Marchant and Sherlock 1984; Carr 1986), leading to operational acceptance, within a limited scope, by the forest industry. The material testing component represents a continued commitment to further advance the erosion control methodology available to the forest sector.

3.1.1 Surface erosion control

Initial research activities were directed at the control of surface erosion from forest roads. Experimental projects (EP) 834 and 818, under W. Carr and S. Homoky, respectively, were concerned with the development and testing of seeding methodology and equipment for use in the forest environment. Hydraulic or slurry seeding (hydroseeding) proved to be highly effective for grass-legume establishment on infertile steep slopes generally encountered on forest roads.

Land Management Report Number 4 (Carr 1980) was written to assist field personnel in the development of an erosion control program. Workshops, seminars, and demonstrations were presented to Ministry and company personnel in each forest region. Many operational trials were also conducted with the cooperation of various forest companies. The results of the demonstration and operational trials have been summarized in a case history format by Homoky (1984). Additionally, this program played an integral role in the development of helicopter slurry seeding for use on steep, inaccessible areas (i.e., landslides). This technique has been accepted on an operational level by the Ministry of Forests and Lands, MacMillan Bloedel, the Greater Vancouver Regional District, and the B.C. Ministry of Transportation and Highways.

3.1.2 Propagation and use of native shrubs

The use of shrubs and small trees is a very important step in bioengineering. Woody plants not only add to soil shear strength, but, when combined with grasses and legumes, create a multi-layer root zone that better holds a slope together. Propagation methodology, planting pattern, and plant density are the principal factors influencing the effectiveness of shrubs for controlling erosion. To date, in the British Columbia forest sector, propagation methodology has received the most investigation, with planting factors receiving less attention due to funding limitations.

In 1980, the Research Branch initiated a native shrub program for use in erosion control. Through a research contract to C. Marchant, EP 863 was begun to investigate propagation methodology for native shrubs and to field test the effectiveness of various species for land rehabilitation. Over 40 native British Columbia tree and shrub species were propagated under EP 863, and a propagation manual was written (Marchant and Sherlock 1984). Several field trials were established from 1981 to 1984. A lack of continued funding has, however, limited the follow-up evaluation. Recent observations from several field trials under EP 818 have indicated some of the more promising coastal and interior shrub species (Table 1).

TABLE 1. Native shrub species suitable for erosion control in British Columbia

COAST	INTERIOR
Alnus sinuata	*Alnus sinuata*
Cornus sericea	*Amelanchier alnifolia*
Lonicera involucrata	*Philadelphus lewisii*
Populus trichocarpa	*Populus trichocarpa*
Salix sp.	*Rosa* sp.
Sambucus racemosa	*Salix* sp.
Spireaea douglasii	*Symphoricarpos albus*

3.1.3 Landslide rehabilitation

Landslide rehabilitation has become a major concern in many forested watersheds in British Columbia. These areas not only represent a potential source of continual sediment production, but also a loss of productive forest land. The majority of the landslide rehabilitation activities have been concentrated on the Queen Charlotte Islands, although two other trials have been initiated in the Vancouver Forest Region.

The Queen Charlotte landslide rehabilitation trials began in 1979 under EP 834 with the cooperation of Crown Forest Industries and MacMillan Bloedel. The first phase of these trials was concerned with controlling surface erosion and sediment production from landslide scars. Helicopter slurry seeding methodology was developed during these trials and successfully tested. The second phase of the rehabilitation involved the establishment of native shrubs, in conjunction with EP 863, to further enhance slope stability. Reforestation with commercial tree species was the final step. This technique is included in Land Management Report Number 36 (Carr 1985). MacMillan Bloedel is continuing this program on the Charlottes as part of a research project funded under Section 88.[1]

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[1] Beese, W.J. 1984. Reforestation of debris slides - progress report. MacMillan Bloedel Ltd., Nanaimo, B.C. Unpublished report. 20 p.

3.1.4 Bioengineering structures

The Ministry of Forests and Lands, Research Branch, is continuing the testing and development of bioengineering techniques under the direction of S. Homoky. A program testing erosion control revegetation mats (ECRM) was established in the Prince George Region in 1983. Several types of ECRM are under investigation with regard to erosion control capability, enhancement of vegetation establishment, and cost-effectiveness. Results from this on-going project are not yet available. Future testing of bioengineering structures will be dependent on funding.

3.2 Recovery of Site Productivity

Soil rehabilitation activities in British Columbia directed at restoring forest productivity on degraded soils began in the mid-1970's. Early results from landing rehabilitation trials in the Cariboo Forest Region, under EP 777, brought about the first landing and skidroad rehabilitation guidelines in British Columbia. These required soil decompaction to a depth of 30 cm, grass seeding for erosion control, and reforestation. The Cariboo guidelines served as a basis for landing rehabilitation guidelines adopted in the other interior forest regions. Historically, enforcement of these guidelines has been lacking in many forest districts, and their effectiveness in meeting the objective of restored productivity has been questioned.[2] Several recent studies have sought to verify the effectiveness of the guidelines and to provide a basis for improved procedures.

3.2.1 Effects of degradation on soil properties

Quantification of the impacts of ground-based harvesting on forest soil properties has recently been completed for both landings and skidroads. The results of the skidroad study (Smith and Wass 1985) and the landing studies[3,4,5,6] are similar. The soil density is generally increased substantially (20%) on landings and skidroads by equipment operation, although increases due to winter logging are less than those associated with summer logging. The increase in soil density persists to a depth of at least 30 cm, and may be more a result of soil scalping than actual soil compaction. The scalping of topsoil dramatically lowers soil organic matter content, as well as the soil nutrient content, especially the concentration of nitrogen, phosphorus, and potassium. An analysis of the impacts on physical and hydrological soil properties is not yet complete.[7]

Some general conclusions from these studies can be made. The increase in soil density from winter logging, although less than that incurred during summer operations, is still great enough to affect future tree growth adversely and must receive equal consideration with rehabilitation of summer-logged areas.[8] Additionally, the replacement of scalped topsoil and the rebuilding of soil nutrient levels must be an integral part of the rehabilitation guidelines. Even if effective soil decompaction is accomplished by ripping or plowing, it is doubtful that the residual soil nutrient levels are adequate to sustain commercial tree growth.

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[4] Carr, W.W. 1986a. Assessment of landing rehabilitation activities in the Prince George East Forest District. B.C. Min. For., Prince George, B.C. Contract Report. 14 p. + appendix.

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[6] McLeod, A.J. and W.W. Carr. In progress. Historical assessment of soil properties and pine regeneration on landings in the Prince George Region. B.C. Min. of For. Lands, Ecology Section, Prince George For. Region, Prince George, B.C.

[7] Ibid.

[8] Carr, 1985.

3.2.2 Advances in soil rehabilitation methodology

A recent evaluation of the standard landing rehabilitation practices used in the Prince George Forest Region demonstrated the need for improved rehabilitation methodology.[9] Soil decompaction using a standard rock ripper failed to create soil conditions acceptable for commercial tree growth. The rock ripper produced only 26% shatter of the soil profile, and the portion of the profile that was affected had reconsolidated to a density in excess of 1400 kg/m^3 within one year. A low soil organic matter level did not allow for the formation of stable aggregates following tillage. An additional finding, related to the low soil organic matter content, showed that total soil nitrogen and available soil phosphorus concentration were below minimum levels recommended by Monenco (1983) for commercial pine growth. Although fundamentally correct, the operational procedures in Prince George need improvement if effective rehabilitation is to be accomplished.

Recent trials in Prince George of a winged subsoiler proved very successful in soil decompaction on landing areas. Soil profile shatter exceeded 80% and the depth of ripping averaged 40-50 cm.[10]

Although soil reconsolidation is still a problem, this is an appropriate piece of equipment for forest soil tillage operations.

The enhancement of soil organic matter content and nutrient levels was a focus of rehabilitation research in Prince George in 1986-87. The feasibility and effectiveness of topsoil replacement was tested as a method to rebuild degraded forest soil. Additionally, based on a promising trial in Vanderhoof District,[11] the use of legumes as a green manure crop was investigated in conjunction with topsoil replacement. It is hoped that this program will solve the rehabilitation problems associated with soil organic matter deficiency.

4 CONCLUSION

The rehabilitation of degraded forest soil in British Columbia has been the subject of considerable research since the mid-1970's. Significant advances have been made in erosion control so that operational programs can become standard components of forest road building and harvesting operations. The adoption of the new coast logging guidelines should provide the impetus for this to occur.

While guidelines for landing and skidroad rehabilitation exist and operational procedures are improving, a reduction in the areal extent of soil degradation caused by ground-based logging should remain a high priority to the forestry sector. The objective of rehabilitation should be to recover as much of the soil's original productivity as possible since full recovery from degraded soils is questionable.

The avenues exist to limit soil degradation and to provide for rehabilitation. However, the enforcement of policies to prevent degradation and adequate funding of soil rehabilitation programs are currently lacking. Until these factors are properly addressed by both the Ministry of Forests and Lands and the forest industry, excessive soil degradation will continue, as will the negative impacts inflicted on all forest resources.

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SESSION 4 REHABILITATION

OBJECTIVES AND EVALUATION OF FOREST TILLAGE[1]

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ABSTRACT

Tillage has gained increased acceptance as a method of rehabilitating degraded forest lands. It can restore some of the productivity of severely compacted or puddled soils by increasing soil aeration and infiltration, decreasing soil strength, and helping restore favorable soil structure. These goals can only be accomplished if the objectives of tillage are known, the right tools are used, and the results are properly evaluated. The ultimate objective of most tillage operations is to improve tree establishment and growth on degraded sites, and the ultimate evaluation of such an operation is determining how well it does so. However, because tillage operations must also be evaluated immediately, on-site determinations must be made of the percentage of compacted soil tilled, size distribution of clods, soil strength, seedbed quality, plantability, and soil porosity.

1 INTRODUCTION

Tillage is defined as the mechanical manipulation of soil for any purpose. In agriculture, it is usually restricted to the modification of soil conditions for crop production (Anonymous 1978). The purpose of tillage in forestry is essentially the same — to modify the soil and thus increase tree establishment, survival, and growth.

Forest tillage can be implemented either to improve existing site conditions or to restore degraded ones. Naturally adverse conditions can be improved by using tillage to control vegetation, improve drainage, incorporate nutrients, or mix soil layers. Restoration of sites degraded by compaction and soil puddling will be the primary focus of this paper.

2 PROBLEMS UNIQUE TO FOREST SOILS

Undisturbed forest soil is typically high in organic matter, low in strength, and high in porosity. These physical features provide an excellent medium for plant growth, with high rates of water infiltration, sufficient gaseous exchange for root metabolism, and a matrix that can be easily penetrated by growing roots.

These favorable soil conditions can be significantly altered by machine travel and log movement over the soil surface during harvesting. Repeated passes can destroy soil structure and decrease pore space. The net result is a decrease in water infiltration rate and aeration and an increase in soil strength, conditions detrimental to plant growth. Reductions in tree growth rates as a result of compaction have been noted repeatedly (Froehlich 1979; Wert and Thomas 1981; Froehlich *et al.* 1986). Compaction caused by machine traffic is routinely ameliorated in agriculture by tillage, a practice that is also becoming more common on forest sites.

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[1] Paper 2120 of the Forest Research Laboratory, Oregon State University, Corvallis, OR 97331.

Forest tillage is being used in many applications. Among them are the tilling of compacted skidtrails (Andrus and Froehlich 1983; Froehlich and Miles 1984). Landings are also occasionally tilled when they are not going to be used until the end of the rotation. Entire harvest units are sometimes tilled when compaction is widespread. Seed orchards and progeny test sites are often tilled after stumps, slash, and vegetation have been removed from them with heavy equipment.

Conditions unique to the forest environment make tillage with agricultural equipment impossible. These conditions include rocky and even perpetually wet soils, as well as the presence of logging slash, stumps, and large roots. A variety of equipment has been used to till forest soils, including disks, brushblades, rock rippers, standard subsoilers, and winged subsoilers (Andrus and Froehlich 1983). Specialized equipment that provides some degree of tillage, but is designed primarily for site preparation, includes roller choppers, furrowers, and bedders (Froehlich 1984).

The effectiveness of forest tillage should be evaluated immediately and over the long term. Immediate on-site evaluations are needed to determine if tools and techniques are having the desired effect. Ultimately, however, the only evaluation that can determine whether tillage is effective is to measure its effect on tree establishment and growth.

3 IMMEDIATE EVALUATION

Immediate evaluation of tillage involves ensuring that the desired changes in soil physical properties are produced and that as much of the compacted soil is tilled as is economically justifiable. Not only must the affected surface area be considered, but also the depth of the compacted soil. Evaluation of these two factors requires that the original extent of soil compaction be known.

3.1 Area and Depth of Compaction

Evaluating the areal extent of compacted soil is fairly simple, especially if done either while equipment is operating or immediately afterward. Generally, with seed orchards, progeny test sites, and landings, all of the area is compacted to some degree during establishment and is therefore tilled. In the case of entire harvest units, criteria must be established as to what degree of soil compaction will be tolerated before tillage is required. These criteria may be based on the number of machine trips across a point, degree of soil disturbance, or some measurement threshold such as percentage increase in bulk density or soil strength. For example, tillage might be prescribed wherever harvest equipment has travelled across a point more than three times or wherever the soil bulk density has increased more than 10%.

Once the areal extent of soil compaction is evaluated, its depth should also be measured or estimated. Depth of compaction can be determined by measuring soil density or soil strength at various depths in compacted areas and comparing those values with similar measurements in noncompacted areas. Depth varies with degree: the more intense the soil compaction, the greater its depth will be. In medium- to high-use skid trails, soil compaction extends to at least 30 cm depth. Wert and Thomas (1981) found that, 32 years after harvest, soil bulk density at 30 cm depths was 16% higher on skid trails than on adjacent undisturbed areas; and Froehlich *et al.* (1985) found that, 1 year after harvest, bulk density at the same depth was 23-44% higher on skid trails than on adjacent undisturbed areas. In a study of two Idaho soils, Froehlich *et al.* (1983) found that the increase in soil bulk density in heavily used skid trails extended beyond the 60 cm depth (Fig. 1).

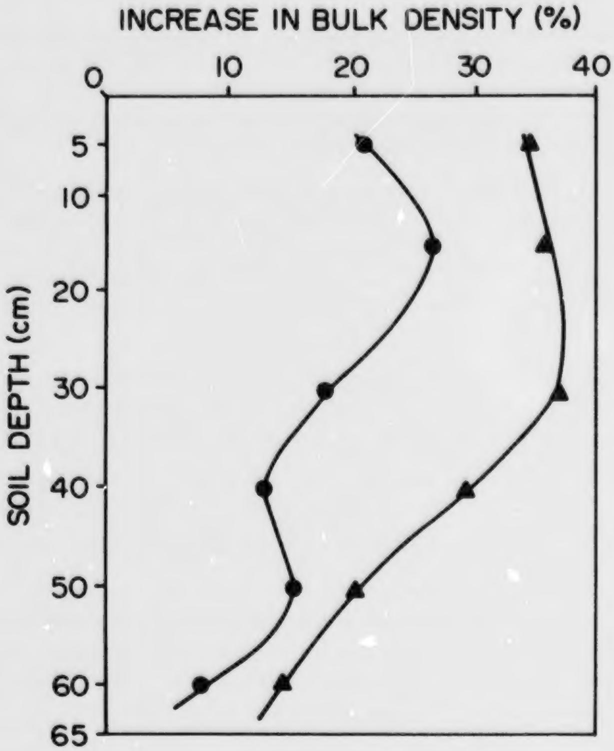

FIGURE 1. Average increase in bulk density with depth on heavily compacted skidtrails on two soil types in central Idaho. Circles represent density profile on Typic Xeropsamment, and triangles represent Dystric Cryochrept.

3.2 Percentage of Soil Tilled

Armed with estimates of the original area and depth of soil compaction, the soil scientist or contract administrator must quickly determine what percentages of this area and depth were actually tilled. The simplest technique to determine depth tilled is to dig a trench with a shovel across a completed pass of the tillage equipment (Anonymous 1977; Andrus and Froehlich 1983). When the soil is only moderately compacted and tillage is reasonably effective, the boundary between tilled and non-tilled soil is easy to distinguish. As the interface between tilled and non-tilled soil is approached, a small hand trowel should be substituted for the shovel. When the interface is reached, digging should be stopped. The resulting profile can be determined by driving stakes on either side of the trench, stretching a string between them, and measuring down from it to the interface. Examples of such profiles are shown in Figure 2.

Once the actual profile of the tilled soil is known, it can be compared with measured profiles of the compacted soil to determine what percentage of the compacted soil was tilled. Andrus and Froehlich (1983) used this technique to determine the relative effectiveness of five tillage implements. Compacted soil tilled varied from 20% of cross-sectional area with a disk harrow to more than 80% with a winged subsoiler (Fig. 3).

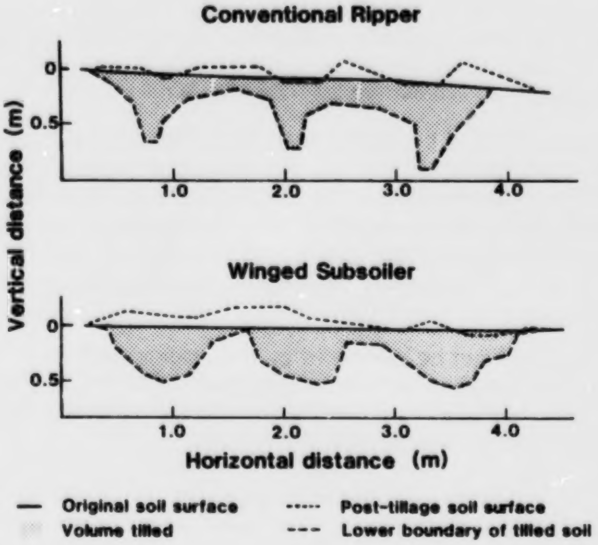

FIGURE 2. Profiles of soil loosened by single passes of a three-tined conventional ripper and a three-tined winged subsoiler. Adapted from Andrus and Froehlich (1983).

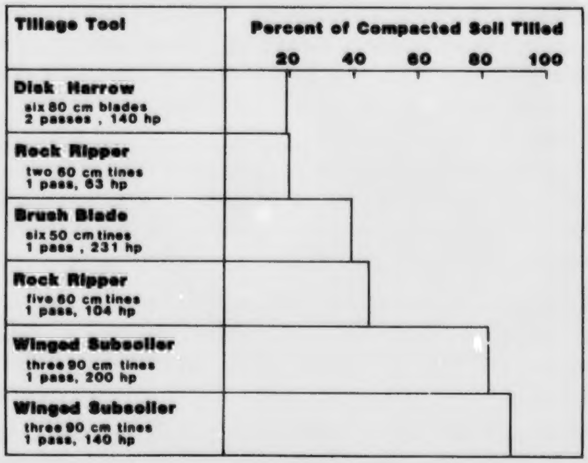

FIGURE 3. Percentages of compacted soil, in cross-sectional area, tilled by six tools in Oregon.

3.3 Soil Porosity and Bulk Density

Soil porosity is the percentage of the total soil volume not occupied by solid particles (Anonymous 1978). Porosity and pore size distribution are soil properties that determine the rate of flow of air, water, and nutrients to plant roots. The decrease in porosity resulting from soil compaction, therefore, has a negative effect on tree growth. Tillage should increase the porosity of compacted soil by lifting and fracturing the compacted soil mass.

Soil porosity can be measured by various methods. Perhaps the most common is to measure the bulk density of the soil. Bulk density is inversely proportional to porosity: Porosity = 1 - Bulk density/particle density. The effect of tillage on soil porosity can, therefore, be determined by measuring bulk density before and after tillage. The degree of restoration relative to undisturbed conditions can be determined by comparing bulk density after tillage to that of a nearby undisturbed area. In recent unpublished work in western Oregon, we found that tillage with a three-tined winged subsoiler reduced soil bulk density of skid trails to the levels of adjacent undisturbed soil (Table 1).

Bulk density of forest soil can be measured by implements such as a sand funnel or nuclear densiometer and with clods and cores. The method used depends on cost, objectives, availability of equipment, and amount of rocks and roots in the soil. Forest soil is extremely variable, especially after tillage, so samples should be either large or numerous.

TABLE 1. Bulk density of undisturbed soil and compacted skidtrails after various tilling treatments on a clay loam soil in western Oregon

	Bulk Density (Mg/m^3) of Soil			
			Compacted and Tilled	
Depth (cm)	**Undisturbed**	**Compacted**	**Subsoiled**	**Subsoiled and Disked**
10	1.00	1.30	0.96	0.91
20	1.04	1.33	1.00	1.00
30	1.05	1.29	0.98	1.03

Measuring bulk density by the clod method (Blake 1965) is likely to underestimate the effect of tillage, because only the density of individual clods is measured. Tillage seldom reduces the density of individual clods but, instead, breaks them up, reducing their size and increasing the amount of pore space between them.

Soil cores (Blake 1965) are often used for such measurements, although the small size of the most common core samplers requires that a large number of cores be taken. Larger core samplers such as those described by Tuttle *et al.* (1984) may be more useful. Additional problems with all hammer-driven core samplers include accidental compaction of the soil while driving the core into the ground, and difficulties in extracting cores when the soil contains numerous rock fragments.

The sand funnel method (Blake 1965) can be used for measuring soil bulk density, although the weight and cost of even-density sand can make this method unattractive. The same general technique is used for the bead-cone method (Flint and Childs 1984), which involves lighter equipment and produces larger-sized samples.

Nuclear densiometers can be used to measure the bulk density of soils containing a moderate amount of rock fragments. They also allow rapid measurements of large samples. These devices have some disadvantages, however, including high initial costs and the emission of hazardous radiation.

Regardless of method used, bulk density of tilled soil should be measured at all depths initially compacted. Surface conditions do not necessarily reflect conditions at a greater depth. The effort required to take measurements below the soil surface should be considered in the choice of a method for determining bulk density.

Besides such measurements, relative porosity can also be determined by measuring the flow of air or water through the soil. This flow can be measured with air permeameters, infiltrometers, and percolation tests. Soil samples can also be analyzed in the laboratory for permeability and hydraulic conductivity.

3.4 Soil Strength

Strength of a soil refers to its resistance to deformation and affects the ability of plant roots to penetrate the soil mass. Roots explore the soil for nutrients, water, and physical support. As they grow, they exert pressure on the soil particles; if this pressure is less than the resistance of the soil, root growth is inhibited. Compaction increases soil strength and therefore inhibits root growth and, ultimately, forest productivity. Tillage should decrease soil strength by fracturing the compacted soil and increasing pore space.

Soil strength can be determined on-site with cone penetrometers (Davidson 1965) and vane shear devices (ASTM 1956) and in the laboratory with various engineering tests (Sallberg 1965). Of these devices, the cone penetrometer most closely simulates the action of plant roots and is perhaps the easiest to use. A recording cone penetrometer (Carter 1967) can even produce a record of soil strength at the various depths penetrated by the shaft. In unpublished work in the central Coast Range of Oregon, we used a recording cone penetrometer to compare the soil strength of undisturbed forest soil, compacted soil, and compacted soil tilled with a conventional three-tined rock ripper (Fig. 4). Soil strength was increased greatly by compaction and subsequently decreased as the soil was loosened by ripping.

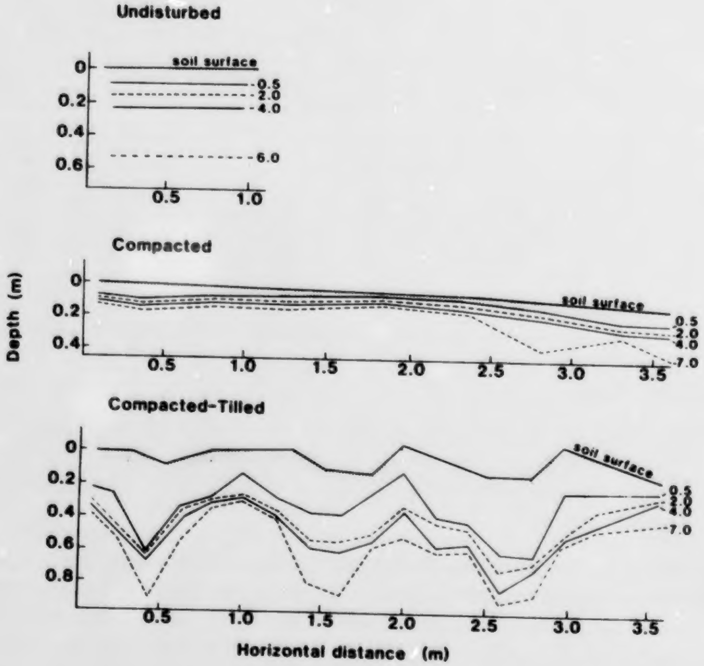

FIGURE 4. Soil strength profiles of undisturbed soil, compacted soil, and compacted soil tilled with a three-tined conventional rock ripper. Lines of equal strength in MPa, as measured by a recording cone penetrometer.

3.5 Soil Structure

Soil structure is easily damaged by machine traffic. Undisturbed structure is dependent on soil texture, porosity, relative geologic age, organic matter content, and biological activity in the soil. A typical undisturbed soil may have loose, granular structure at the surface and a more blocky structure beneath the surface. Compacting such soil can create a platy or massive structure.

Tillage should break up compacted soil and produce loosely packed, small soil aggregates (clods or peds), which are more favorable for plant roots. Excessive tillage, however, can destroy aggregates and harm the soil structure.

The effectiveness of tillage in restoring favorable soil structure can be assessed by determining the size class distribution of soil clods (Kemper and Chepil 1965). Such a determination requires that a soil sample be shaken through a set of nested sieves. This must be done delicately, as soil clods can break into smaller pieces as they are shaken. An example of the results of clod sieving can be found in Table 2. After tillage with a winged subsoiler, clods greater than 50 mm in diameter comprised 14% of the total weight of the loam sample and 40% of that of the silty clay sample. On the silty clay soil, a standard subsoiler produced more large clods than did a winged subsoiler or disks.

In addition to their size, the stability of clods is also important (Kemper 1965). Large, hard clods are unlikely to break down in the field and may inhibit plant root growth. The stability of soil clods can be indexed by wet-sieving them. The degree to which the clods break up when gently sieved under water indicates their relative stability under field conditions. More simply, clods can be soaked in water or observed in the field over a winter season to determine the degree to which they slake and break apart.

TABLE 2. Percentage of total sample weight in variously sized clods in two soils tilled by several implements. Soil moisture content at the time of tillage was 30% by weight.

Soil Texture and Tillage Implement	Percent of Total Weight by Sieve Size					
	50 mm	**25 mm**	**10 mm**	**5 mm**	**2 mm**	**Pan**
Loam						
Winged subsoiler	14	8	11	10	16	41
Silty clay						
Winged subsoiler	40	8	9	9	12	21
Subsoiler	53	8	10	8	8	13
Disks	38	10	13	10	11	19

3.6 Seedling Establishment

The restored productivity of tilled forest soil will not be seen to be completely utilized until trees are established on it. Tillage should provide a soil condition suitable for seedling germination and establishment or for successful transplanting. The suitability of the soil for regeneration should therefore be evaluated immediately after tillage.

Soil conditions required for seedling germination and establishment are somewhat more stringent than those required for successful transplanting. The best seedbed for Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, and most other conifers is bare mineral soil, though an organic surface layer may be suitable for western hemlock, *Tsuga heterophylla* (Raf.) Sarg. (Greaves and Hermann 1978). The soil surface must be sufficiently well tilled to reduce its resistance to root penetration. It must not be too rough, or the seed might be buried in surface cracks or by soil sloughing.

Soil conditions required for hand-planting seedlings are not overly demanding. Tillage should loosen the soil at least down to the desirable depth for seedling roots; otherwise, shallow planting is likely.

4 LONG-TERM EVALUATION: A RESEARCH NEED

The effects of forest tillage on the physical properties of soil are not static, as the tilled soil mass will tend to settle and adjust in response to natural forces. Gravity, raindrop impact, wetting and drying cycles, diurnal and seasonal freezing and thawing cycles, and biological activity will alter the soil's physical properties over time. Remeasuring these properties several years after tillage is therefore desirable. In recent unpublished work in southwestern Oregon, we found that, three winters after tillage, soil loosened by a three-tined subsoiler maintained a bulk density 0-6% higher than that of undisturbed soil; and non-tilled soil between rip lines remained 15-19% denser than undisturbed soil (Table 3).

Plans for evaluating long-term effects on tree establishment and growth must be made before tillage is completed. A simple comparison of regeneration rates on tilled and nearby untilled soils should be made. The two soils should be as similar as possible in original degree of compaction and other environmental characteristics.

Seedling establishment should also be evaluated on areas where tillage is intended to produce a favorable seedbed for natural regeneration or artificial seeding. In a greenhouse, Hatchell (1970) grew loblolly pine, *Pinus taeda* L., from seeds planted in soil cores taken from compacted forest soil in the southeastern United States. He found that seeds in the compacted cores had an establishment rate of 75%, while those in compacted cores that were hand-loosened had an establishment rate of 90%. After one year, the resulting seedlings had average dry shoot weights of 184 mg in compacted cores and 211 mg in loosened cores.

TABLE 3. Bulk density of undisturbed soil and compacted skidtrails tilled with a three-tined subsoiler. Data were taken three winters after tillage on a site in southwestern Oregon.

	Bulk Density (Mg/m³) of Soil		
		Compacted and Subsoiled	
Depth (cm)	**Undisturbed**	**In Rip Lines**	**Between Rip Lines**
10	1.03	1.03	1.18
20	1.07	1.10	1.27
30	1.12	1.19	1.29

When nursery stock is transplanted, its survival and growth rates on tilled and non-tilled soil should be determined. In New Zealand, Guild (1971) examined survival and growth of 3-year-old radiata pine, *Pinus radiata* D. Don, in non-tilled soil and soil tilled 45-60 cm deep with two standard rock rippers. He found a statistically significant increase in average survival — 47% on non-tilled soil and 85% on tilled soil. Growth rate on the tilled soil was significantly greater on only two of four sites examined; the other two sites showed no difference in growth rates. Berg (1975) also worked in New Zealand, planting 1-0 *Pinus radiata* in non-ripped soil and soil ripped with a single tine to a depth of 45-60 cm. He found that, after three years, survival averaged 55% on non-tilled soil and 85% on tilled soil; mean height was 75 and 102 cm, respectively. On fertilized plots established at the same time, the effect of ripping on survival and growth was somewhat diminished. In another study in New Zealand, however, Somerville (1979) found no significant difference in height or diameter growth of 11-year-old *Pinus radiata* growing on ripped and non-ripped soil, although the trees growing on ripped soil had better root anchorage.

Berry (1979), working in the southeastern United States, found that subsoiling increased volume growth of 5-year-old *Pinus taeda* by 19% and of shortleaf pine, *Pinus echinata* Mill., by 38%. Whitaker (1983) grew *Pseudotsuga menziesii* and white fir, *Abies concolor* (Gord. & Glend.) Lindl., for 226 days in a growth chamber in soil cores removed from subsoiled and non-tilled skidtrails from southwestern Oregon.

She found that *Pseudotsuga menziesii* had shoot and root weights 40% higher in soil cores from subsoiled skidtrails than in those from non-tilled trails (Fig. 5). *Abies concolor* showed a 60% increase in shoot and root weight in subsoiled cores (Fig. 6).

Generally, these studies indicate that even limited tillage enhances seedling establishment and growth. However, not all tools commonly used fracture a satisfactory amount of soil in a pattern conducive to root growth. Furthermore, tillage must be designed to treat a known problem, and it must be done under proper moisture conditions if desired results are to be achieved. We anticipate that more effective tillage would result in even better tree growth. Future research should focus on ascertaining that tillage has been adequate and on evaluating long-term growth response.

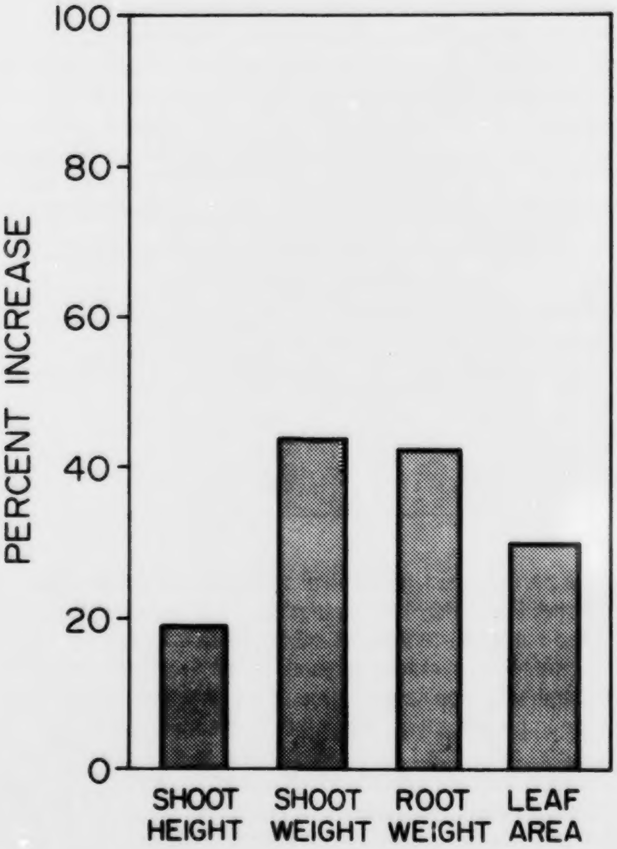

FIGURE 5. Percentage increase in growth of *Pseudotsuga menziesii* seedlings in cores from tilled skidtrails over that in cores from non-tilled ones. Comparisons were made after 226 days in a growth chamber.

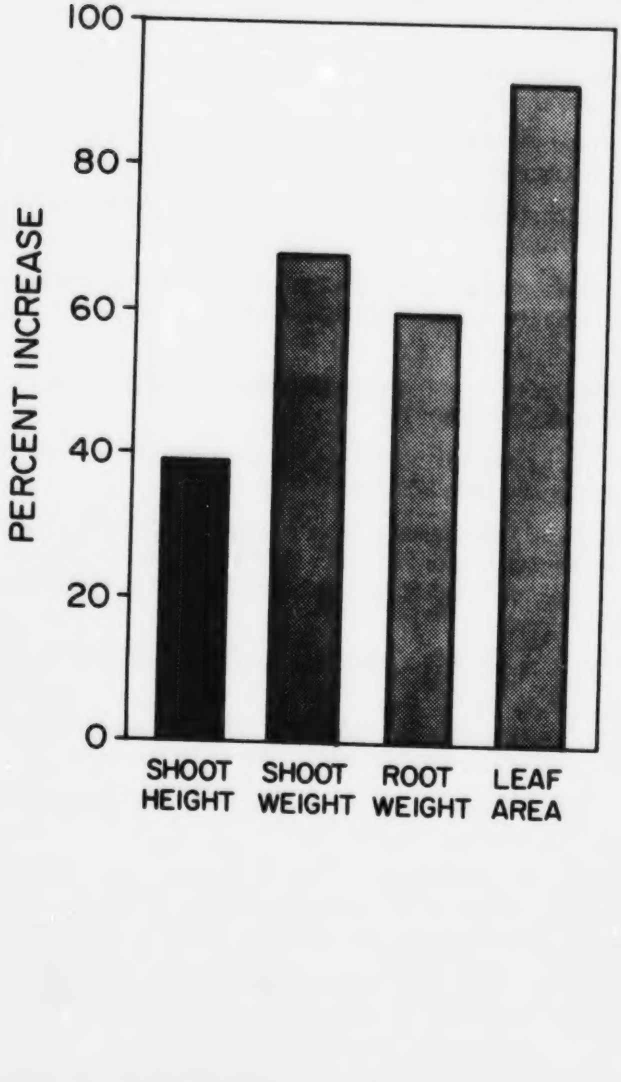

FIGURE 6. Percentage increase in growth of *Abies concolor* seedlings in cores from tilled skidtrails over that in cores from non-tilled ones. Comparisons were made after 226 days in a growth chamber.

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SESSION 5

Economics of Forest Soil Degradation and Rehabilitation

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SESSION 5 ECONOMICS

ECONOMICS OF FOREST SOIL DEGRADATION AND REHABILITATION

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ABSTRACT

The problems associated with forest harvesting and soil degradation can be characterized as "external" to the forest industry — impacts on water quality, fish and wildlife, recreation, visual and related effects — and "internal" — loss of future forest productivity. In dealing with external impacts, we are incurring significant costs in forestry by modifying harvest practices to reduce negative impacts on (or increase the benefits realized from) other resource uses, but we have poor perceptions of the resulting benefits.

In terms of internal impacts, the actual effects on forest productivity appear to be highly variable and not easily predictable. A significant research effort, aimed at improving predictive abilities, is currently underway. Economics has relatively little to contribute to this research, although an appreciation of how the impacts can be incorporated in economic analysis may be of some interest to research design.

1 ECONOMICS OF FOREST SOIL DEGRADATION - EFFECTS

1.1 External Effects

Forest soil degradation would, in large measure, fall into the category of effects which economists describe as "externalities." These are the "spillovers," if you will, the unintended side-effects, good or bad, which follow from a primary economic activity, such as forest harvesting. Some examples might be the impacts of soil erosion on water quality and sedimentation in streams which may have adverse direct effects on fish populations and habitat, and potential consequences for both sport and commercial fisheries. There are also widespread concerns over the more general effects of forest harvesting on recreation, wildlife and wildlife habitat, and visual and aesthetic amenities. The economic problem is that those engaged in the primary activity generally do not bear the consequences of their actions directly, and so they have no direct incentives to modify their practices and reduce the "externalities" which they cause.

These kinds of problems are hardly unique to the forest industry. They are associated in one way or another with many economic activities throughout the economy. We have, for example, noise and air pollution and unsightliness associated with manufacturing activities, and, increasingly, air and water pollution associated with various agricultural endeavors.

1.2 Internal Effects

It appears from a brief review of the forest soil degradation problem that, in addition to the kinds of "externalities" about which we are accustomed to hearing concerns, there are probably equally important "internal" effects. Simply put, these effects are that degradation of soils associated with taking the first forest harvest may adversely effect the growth of successive crops. I understand that within the forest industry and profession there is growing concern about these "internal" effects, as we move into more sensitive lands, i.e., steeper slopes, higher elevations and more difficult terrain.

I refer to these effects as "internalities" because, in the simplest economic model, it would be expected that those involved in the primary activity of forest harvesting would suffer the consequences of these adverse effects. Hence they would have all the right incentives to modify their current practices, reduce these adverse effects, and bring things into balance. Thus the solution to the problem or problems is "internal" to the economic calculations of the primary economic actors.

1.3 Cost-Benefit Responsibility

Unfortunately this is far too simple a view of the issue. To begin with, those involved with harvesting the initial crop apparently do not have a good understanding of just how their actions today affect soils and how that affects future forest productivity. Secondly, even if they did have an adequate understanding of these implications, the ultimate consequences are generally so far in the future (50 or more years before we take the next cut) that it is perhaps expecting too much to think that those taking the initial harvest could properly "bring things into balance." Finally, with most of our forests on Crown land, those doing the harvesting do not have a direct ownership interest in the land, and it is not clear that they would bear adverse future consequences in any event.

To an economist the correct resolution of both the "internal" and "external" aspects of the soil degradation problem is the same. The economists' prescription, which is infuriatingly clear and simple, is that it makes sense to incur costs in forest harvesting today up to the point that those costs are matched by increased benefits, either in terms of other resource uses (watershed values, fish, recreation, etc.), or in terms of future forest harvests. The solution is simple, says the economist, "... equate at the margin," or incur costs only up to the point where they are just matched by offsetting benefits. You will then have the socially most desirable mix of immediate resource extraction benefits and "conservation" benefits.

Such advice is, of course, worth about what I am being paid for it today. The problem is that however elegant, clear and logically correct the economic model, we do not at present have the necessary knowledge to implement this solution.

1.4 Regulation and Prescription

It was stated earlier that these problems are hardly unique to the forest industry. They have been with us for years throughout the economy. By and large, the solutions that we have found workable are not "economic." We rely largely on regulation and prescription. Zoning and land use planning regulations are a simple and widespread example of how we try to control spillovers from various types of land use, industrial, commercial, agricultural, residential, etc. We do not ask whether the costs which regulations impose on one group of players in the economy are matched by offsetting benefits to others. It was probably recognized long ago that nobody is equipped to answer such questions and we have proceeded with the most expeditious solutions.

Similarly, when it comes to discharges of byproducts into the air or water, we generally rely on regulation, not economic optimization. This often results in what to an economist are frustrating impositions of clearly wasteful regulations. It may be economically rational to control discharges to waterways in our heavily populated areas where concentrations of pollutants may become high, and important alternative uses of water may be affected. It is terribly frustrating, on the other hand, to see millions of dollars being spent adhering to the same standards in remote areas to prevent what are, at most, absolutely trivial impacts.

Despite the outright waste which is often involved in the regulatory approach to externalities generally, one has to regard it as a cost of maintaining some semblance of order in our very complex economic systems.

1.5 Mitigating Measures

I have said that to an economist the solution to both the external and internal impacts associated with forest harvesting is really the same. Since we have been concerned with the external impacts for some time now, it is worth asking how well we are doing in dealing with them.

My answer would be: not very well at all. I do not want to be misinterpreted as saying that we are not exercising adequate precautions with respect to our water, fish, wildlife and recreation resources. On the contrary, we go to great lengths to modify our logging practices and incur very substantial costs in order to protect other resources and resource users. I would say that we are not doing this very well because, while we may have some ideas of the costs involved, we are very poorly informed as to the resulting benefits to other resource users.

As to the costs of trying to cure the industry's externalities, it has been variously reported to me that these amount to some $10/m^3$ harvested — that is to say logging costs are higher by roughly $10/m^3$ because of the restrictions imposed in order to prevent or mitigate external effects. If that is correct, and with the British Columbia forest industry harvesting upwards of 70 million m^3/yr, it indicates we are spending in the order of $700 million/yr trying to mitigate external effects.

That is a very large sum of money, by and large being spent unknowingly. It is spent unknowingly because, under our stumpage system at normal market times, the money is not that of the parties doing the harvesting. It is, in effect, coming out of general revenue via the stumpage system.

Despite the estimated magnitude of these expenditures, I have yet to see any evidence that we are getting $700 million/yr in the form of enhanced benefits or value from other resources. I am not suggesting that we should abandon our efforts to control externalities, but it is certainly worth taking a hard look at how we are approaching this at the moment. Some of the material I have seen from logging folio plans indicates to me that the costs of accommodating or protecting other resource interests are indeed significant. One has to at least question whether the benefits which we as a society enjoy in return justify these costs.

This is a situation which puts me in mind of remarks attributed to H.R. MacMillan many years ago. Commenting on the problems with utilization standards in the woods he is reported to have said that, from time to time, they would gather the logging crews together and exhort them to stop wasting wood. Subsequently they would check up to see if standards had improved. To their horror they would find that the crews were no longer wasting wood — but on a grand scale they were now wasting capital. I suspect we may be doing the same thing today. We have, for example, felt a need to stop wasting "wildlife" and are instead wasting the public's capital. What is frustrating about this is that in many respects the application of economics to rationalize these efforts to deal with externalities is simpler and could be more direct that when we address soil degradation. The effects are at least more immediate, and while there are problems with valuation, they are not intractable. I have digressed with this discussion of how we are dealing with externalities because, from an economic perspective, the way we deal with them and the way we deal with the "internalities" of soil degradation should be the same. I would like to think that in the latter case, with the serious research now underway, we may be able to handle things more effectively.

2 ECONOMICS OF FOREST SOIL DEGRADATION: PLANNING

Soil degradation, as it affects the future growth of the forest, is a serious and growing concern among foresters. In my review of the abstracts for this conference I found the physical mechanisms to be varied. They include mass wasting, to which I find some alarming reference (a loss of 50% of productive capacity over an 80-year rotation); soil disturbance and compaction; and roads and landings.

While these physical mechanisms are varied, the consequence that is of concern is uniformly the loss in productivity and the reduction in future harvests. This may be somewhat of an over-simplification, but to an economist that is the essence of the problem. It is effectively a shrinking of our forest resource base in the future.

Prospects of a significant reduction in forest productivity can easily be alarming. If it is as serious as some references indicate, I would expect the forestry profession to be at least as concerned about this problem as it has been with the withdrawal of land from provincial forests for non-forestry purposes.

2.1 Timing

The problem I have as an economist in dealing with the importance of soil degradation is that we are not losing an existing stock of trees. We are losing, or think we are losing, trees or wood fibre in the distant future. To an economist trying to deal with the importance of such losses, it generally means placing a monetary value on them. I will outline some of the problems we face in dealing with potential losses of this nature.

2.1.1 Discounting

Some of our most difficult problems are associated with timing — the need to discount, and the need to forecast. Discounting is a very serious aspect of dealing with the forests of the future. It is the process used in economic and financial analyses to allow for the "time value of money" or the "social rate of time preference." It attempts to account systematically, through the interest or discount rate, for the fact that a given quantity of a resource which you will only have in the future is worth less than that same quantity of resource if it is available to you today.

The discounting process is very logical and sensible, but, as the interest rate used in discounting rises, it is a process which deals harshly with the future. For example, if my discount rate is 4%, I would value $1 worth of a resource which I will get 50 years from now at $0.14 today. If the resource will be available to me 40 years from now, instead of 50, I would value it at $0.21. As this indicates, a difference of only 10 years in timing leads to a difference of 50% in the discounted value.

Choosing the appropriate discount rate also has a large bearing on the results. Using an 8% rate rather than 4% (8% appears to be in favour for public investment projects), the value of $1 in 50 years is only $0.02, and the value of $1 in 40 years is $0.05.

Another way to look at this is to say that these figures give some guidance as to how much can rationally be spent (sacrificed) now in order to avoid a given cost or sacrifice in the distant future. The answer, if you believe in discounting, is not really very much. The problem which I have tried to demonstrate is that the answer will vary by orders of magnitude depending on just how far in the future you expect the cost to be incurred, and depending on the discount rate which is judged to be appropriate for the analysis.

2.1.2 Forecasting

Probably more contentious than the discounting process is the other key aspect of dealing with values in the future, the need to forecast. If we are going to have less wood fibre to harvest 40 or 80 years from now, what is its value likely to be at that time? How significant is that loss? There are some very long-term trend analyses which have indicated that the value of stumpage has at least remained constant over time, and perhaps has even increased in real terms by 1 or 2% per year. But it places a heavy burden on a forecaster to ask for a projection of the value of wood fibre four to eight decades from now.

If we are going to establish the importance of reduced forest productivity, using a conventional economic approach, these kinds of problems with discounting and forecasting — arising from the timing of impacts — have to be dealt with. In my view they are serious problems.

2.2 Valuation

In addition to these problems of timing, there are fundamental problems with valuation. I mentioned the difficulty with forecasts. That difficulty assumes we are dealing with a standard, commonly marketed commodity, such as lumber. But in valuing forest productivity, or changes in the volume of standing timber in British Columbia, we are not valuing a commonly marketed commodity. We are valuing a commodity which is basically withheld from normal market forces between buyer and seller and allocated instead under our very complex tenure system of TFL's, Forest Licences, TSHL's, and TSL's.

It would be convenient to suggest that the stumpage paid to the Crown reflects the full economic value of the standing timber. But the amount which is received in stumpage is constrained by other objectives which the government pursues through the tenure system; so, it is not at all clear that stumpage alone reflects the full value of Crown timber.

This is somewhat analogous to what are referred to as "tax expenditures" in the national accounts. The government may be entitled to a tax revenue of $100 000 from a particular firm, for example, but, if that firm makes certain investments or commitments, the tax payable may be reduced to $50 000. In such cases, we would like to assume that what the firm has done to earn the tax reduction is worth at least $50 000. If that is so, the end result is the same as if the government had received $100 000 and then spent $50 000.

The problem with applying this analogy to Crown stumpage is that we do not know how much potential revenue has been given up as a result of various policy constraints, and therefore we do not know what the real economic value of standing timber is. There may be some suitable proxies, if we could look at the market value of private timber, but that kind of information is not readily available.

This fundamental problem with valuing Crown timber is a serious challenge. Given this, and the problems associated with timing, I hope you can appreciate the difficult problems confronting economists in trying to deal rationally with the importance and value of the consequences of forest soil degradation.

3 ECONOMICS OF SOIL REHABILITATION

3.1 Rehabilitation Versus Prevention

I have not discussed soil rehabilitation, but that is obviously the other side of the coin. Having recognized problems, the forestry profession has already started to look for solutions. Those solutions can be of two kinds: preventative, where you modify logging practices so that problems do not arise; and rehabilitative, where you take steps to correct problems after harvesting. Both solutions involve costs.

From what I can see of the research that is currently underway, there is considerable focus on trying to determine just how serious the consequences of the various forms of soil degradation are. It may be some time before the answers start to emerge. At the same time, there is work underway to develop methods of rehabilitation. I expect we will arrive at a point where we know more about how to prevent soil degradation, and the costs required to do so, than we will about the real long-term consequences of soil degradation and the resulting future costs.

If and when we get to that point, there are two choices. One is to proceed with the rehabilitative/mitigative measures on faith: whatever the cost, it must be worth it. The other is to try and be a little more rational, and at least, ask the economic question: is it worth it? Are the resources we sacrifice now (the costs) at least equalled by the value of the gains (the benefits) we will realize in the future?

I have indicated that economists face some serious problems in trying to answer that question, but I would not like to see the effort abandoned. The last thing I would want to see is for the industry to be launched on a major program of expensive restrictions and prescriptions, in order to offset future costs of undetermined magnitude. There are some challenging areas of economic research here, and I would like to see those challenges pursued.

3.2 Allowable Cut Effect

An alternative approach which I have considered, but am inclined to abandon, is to try and translate the long-term consequences into more immediate, and more easily quantifiable, effects. What I have in mind is the allowable cut effect (ACE), as it is commonly called.

If, in the view of the Chief Forester, the potential loss in forest productivity is serious enough, he may have to adjust downward his estimates of Long Run Sustained Yield, and hence the annual allowable cut (AAC). A reduction in AAC leads to immediate loss of harvests, forest revenues, employment and related economic activity. If this translation can be made, then we have much more readily quantifiable consequences to deal with, and some of the serious problems associated with long-term forecasting and discounting can be partly avoided.

I am inclined to abandon this approach because my understanding is that, by and large, we are still working our way through and liquidating old-growth stands or timber in British Columbia. When the old growth is gone we will encounter the "fall-down" in shifting from high volume, old-growth stands to the lower volume, younger stands of successive crops. A loss in productivity due to soil degradation may mean that the fall-down is more serious than it would otherwise be. However, about the only way we have of easing the fall-down is to prolong the period of transition by slowing the rate of cut of the remaining old-growth timber (and to an undetermined extent through silviculture). It does not appear to me that it would be economically prudent to further reduce today's AAC to accommodate estimates of a greater fall-down in future, when in most areas that future is still 30-80 years away.

For these reasons, while I initially felt there would be some merit in dealing with the consequences of soil degradation through ACE, I am less optimistic now. As before, however, I would not like to see this idea abandoned until it had been given a more thorough scrutiny. Perhaps when we have a better picture of the likely consequences of soil degradation we may be in a better position to reconsider this approach to economic evaluation.

4 CONCLUSION

I have tried to keep the preceding remarks general, my goal being primarily to explain that the economic aspects of forest soil degradation are not simple to deal with. It may be time, now, to initiate some serious research into the economic implications of soil degradation. There might then be some decision aids available when the time comes to decide whether to commit to major costs to deal with soil degradation.

SESSION 5 ECONOMICS

ASSESSING LONG-TERM COSTS OF FOREST SOIL DEGRADATION

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ABSTRACT

Any tree harvesting activity is bound to affect the forest soil. In particular, the harmful effects of roads and landings have been quantitatively assessed. The economic implications of such impacts have not yet been thoroughly explored. Possible soil degradation is ignored even in most calculations of the value of a site in terms of its potential to generate revenue from future tree harvests. In this paper, the effect of soil degradation caused by roads and landings will be incorporated into such calculations. The results will be used to highlight the critical role of the discount factor in determining the importance attached to soil conservation. In particular, it will be shown that a private land owner can easily face economic incentives that make minor gains in immediate revenues sufficiently rewarding to outweigh large reductions in the value of the site for producing revenue from future tree harvests.

1 INTRODUCTION

It has been argued that public ownership of forest land is responsible for the inadequacy of soil conservation and reforestation programs. The argument goes roughly as follows:

If only the people who stood to make a profit from cutting trees also owned the land, then their incentives would change. A reduction of the potential for a site to generate future revenues would decrease the value of the land. Hence, the owner would have the incentive to care for the future productivity, and extensive government regulations would not be needed.

This paper examines the strength of these economic incentives. Other factors influencing the quality of forest land management, such as a desire to preserve the aesthetics or the quality of streams on one's land, will not be included. The procedure will be to follow the commonly accepted practice, proposed by Faustmann (1849), of assuming that an owner will maximize the present net worth of the flow of revenues generated by harvesting trees from his land. This present net worth, usually called the soil expectation value, will be adjusted to account for potential catastrophes such as fires, and then for declines in soil productivity attributable to roads and landings. Results of sample calculations will be used to examine the economic incentives faced by a private landowner.

2 THE SOIL EXPECTATION VALUE

The soil expectation value (SEV) is the discounted present net worth of the stream of future incomes generated by harvesting trees in perpetuity from a site. Samuelson (1976) has argued forcefully that managers of forest land ought to maximize this value, as opposed to, for example, maximizing sustainable yield. This strategy is unpalatable to some foresters because it involves discounting future harvests. This discounting causes a shortening of the rotation period below that which would produce a maximum sustainable yield. However, the reduction in sustainable yield is usually calculated to be relatively small.

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[1] This research was completed while the author was visiting the Department of Biology at the University of Ottawa.

Others criticize the strategy of maximizing the soil expectation value on the grounds that it involves an assumption that the owner will continue to hold the land forever. In reality, he may sell the land at any time. This possibility, however, is of no consequence in determining the optimal harvesting strategy as long as the selling price for the land is the same asthe soil expectation value. This value is the price that a buyer would be willing to pay if his sole benefit from owning the land were to generate revenue from timber harvests.

A third, much more serious criticism of the approach is that traditional calculations of the soil expectation value depend on an assumption that future rotations will behave just like the present one. This assumption includes the bold assertions that no fires or other calamities will ever occur on the site, that prices and costs will remain constant, and that the soil productivity will remain unchanged in future rotations.

Howe (1979) has briefly explored the impact of predictable trends in prices. Routledge (1980) has shown that unpredictable fluctuations in prices (as customarily modelled by economists) have no impact on the optimal rotation age. Martell (1980), Routledge (1980), and Reed (1984) have examined the impact of fires and other potential catastrophes on the soil expectation value. It can be surprisingly large. For example, consider a jack pine stand subject to about one fire, on average, per century. With a discount rate of 2%, the risk of fires can reduce the soil expectation value by 30% or more (Routledge1980).

3 THE IMPACT OF SOIL DEGRADATION

How large an impact might soil degradation have on the soil expectation value? A dynamic programming technique has been developed by Routledge (1986) for answering such questions. The technique will be used here to assess the consequences of declines in productivity caused by the construction and use of skid roads and landings.

Soil degradation can take many forms, such as nutrient depletion, compaction, scalping, and mass erosion (see Cole *et al.* 1967; Borman *et al.* 1968; Clayton 1981; Stark 1982; Ballard 1983; Carr 1983; Timmer *et al.* 1983; Fisher 1984; Froehlich and McNabb 1984; Neary *et al.* 1984; Knight *et al.* 1985). Skid roads and landings are known to produce marked reductions in soil quality. It has been estimated that such factors as scalping and compaction can reduce growth rates (even when prorated over the entire site) by as much as 15% (see Carr 1983 and Froehlich and McNabb 1984).

It will be assumed in the following discussion that such a loss is permanent. To be on the conservative side, the reduction in growth rates will be assumed to be only 10%; i.e., for the rotation immediately following the first use of these transportation facilities, the stand is assumed to take 10% more time to reach a specified size than it would have in the absence of the ill-effects of the skid roads and landings. During the second harvest, it is assumed that the same skid roads and landings will be reused, and their productivity will revert to the state they were in after the previous harvest. This state of affairs is assumed to be repeated during each rotation.

Consider the owner of a jack pine stand, the initial growth function of which is given in Routledge (1986) as follows:

$$R(t) = -21.7195 + 0.8112t - 0.002907$$

The owner is about to harvest the stand. His planned logging operations will cause the decline in future productivities described above. If he is facing a 10% discount rate, then the decline in the soil expectation value caused by his logging operations would be a substantial 34%. The reason for the large reduction is that the decline in productivity would cause a postponement of future harvests. His large 10% discount rate makes this delay very costly.

However, this massive reduction would matter very little to him because with such a high discount rate, these future harvests are not nearly as valuable to his as the one he is about to reap. The percent reduction in the total of the value of this harvest and the soil expectation value is only about 1%. Hence, a private landowner faced with a high discount rate is hardly concerned at all about a permanent reduction in the soil productivity. If a less damaging operation were to cost just over 1% more than the one he is contemplating, then he would still find it too expensive.

The incentive to preserve the soil productivity is somewhat greater for an owner with a moderate discount rate of 2%. For the situation described above, he would value his loss of future revenues at about 5% of the total of present and future revenues. By contrast, the maximum sustainable yield is reduced by about 12-13%. Hence, a manager attempting to maximize the sustainable income from the site would recommend harvesting systems that left the soil productivity intact as long as the extra cost did not exceed about 12-13% of the net revenue generated by the cheaper, but more damaging operation.

4 CONCLUSIONS

Soil conservation is not likely to be economically attractive to a private owner of forest land. He would get a higher financial return by investing his money elsewhere. Even a moderate discount rate of only 2% can encourage management practices that leave the soil severely degraded after only one or two rotations. Foresters concerned with maximizing the sustainable yield will reach substantially different conclusions about the use of efficient, but potentially damaging logging practices.

The essence of the conflict between these two perspectives is the value of the discount rate. Managing for maximum sustainable yield makes sense only if the rate at which distant harvests are discounted is zero. This conflict is not evident in traditional evaluations of the soil expectation value because the potential for soil degradation is ignored.

Management for maximum sustained yield is a substantially different task from management for discounted present net worth. The latter can be achieved by essentially ignoring distant rotations. To achieve the former, we need to examine the possible long-term consequences of proposed logging practices. Predictions of consequences for distant rotations are obviously highly speculative. In Routledge (1986), a method is proposed for putting reasonable limits on the soil expectation value in the presence of uncertain predictions for future rotations.

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SESSION 5 ECONOMICS

SOIL DEGRADATION: COSTS OF REHABILITATION VERSUS COSTS OF PREVENTION

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ABSTRACT

Long-term soil degradation results primarily from surface and mass erosion and from compaction caused by forest management practices. Road construction and machine activity are primary causes. Degradation of forest soils reduces site productivity and can result in large rehabilitation costs through requirements for slope stabilization, tillage, and road maintenance. Damage to fish habitat and water supplies is costly to repair; frequently it is irreparable. Forest managers have a responsibility to consider resource values other than the short-term economic return from timber extraction. Fish habitat, domestic and agricultural water supplies, and aesthetics are difficult to value in monetary terms. However, resource uses other than timber frequently have important social values that are adversely affected by degraded soil. The most cost-effective means to control soil degradation is prevention through holistic planning which considers all forest values. Planning activities can identify unstable terrain so that degradation can be avoided. Complete field data collection will help to ensure stable road locations and effective design and layout of all aspects of harvest systems. Comprehensive planning costs will be less than the costs of lost timber production and environmental damage caused by soil degradation.

1 INTRODUCTION

Timber extraction activities in British Columbia can cause extensive soil degradation, frequently resulting in large rehabilitation problems (Hammond 1984). The real costs of degradation and rehabilitation need to be examined. Most of the degradation which occurs from logging activity can be prevented. However, prevention requires a change of perspective on the part of forest managers and loggers.

Until recently, forest managers have not seriously considered the costs of soil degradation. Logging was taking place in areas of few conflicts with other resource values and it was assumed that there would always be a supply of quality timber, regardless of how current operations were conducted. The problem of lowered productivity from degraded forest soils was debatable and its solution was postponed. Today, however, foresters realize that the supply of quality timber is finite. Current logging operations are likely to conflict with other values such as domestic water use, fish habitat, tourism, and visual aesthetics. Where logging conflicts with other values, soil degradation becomes socially unacceptable to the public.

This paper examines some of the types of soil degradation resulting from timber harvesting activities in British Columbia; the concept of values other than timber; the social and economic costs of rehabilitating soil degradation; and the importance of planning as a cost-effective means of avoiding degradation.

2 SOIL DEGRADATION: SOME CAUSES AND EFFECTS

Soil degradation in managed forests can occur through surface and mass erosion caused by road construction or clearcut logging practices. Degradation also includes soil compaction caused by machinery. In the case of soil movement resulting from clearcutting or road building, soil degradation can cause problems on-site and frequently off-site, sometimes far from the area where harvesting activities actually took place.

2.1 Surface and Mass Erosion

Soil erosion is a natural process in forested watersheds. However, forest harvesting increases the level of both surface and mass erosion. Surface erosion is increased through the exposure of mineral soil, concentration of runoff by roads and skid trails, and traffic over inadequately surfaced roads. Mass erosion is increased by root decay, yarding disturbance, fringe blowdown, debris accumulation in gullies, and roads. The degree to which harvesting increases erosional levels is related to soils, climate, type of logging, level of planning, and operator performance (Jeffrey 1968; Froehlich 1978; Rice and Datzman 1981; Carr 1983a; Poulin 1983). Sidle *et al.* (1985) cited a range of mass erosion studies showing logging-related increases in the rate of mass erosion (cubic meters per hectare per year) of 28-348 times the natural level.

Surface erosion from forest road construction can be caused by road surface wash, sediment from sidecast during and after construction, and road cutslope sediment transported by ditch flow. Removal of sediment from eroding road surfaces may also adversely affect road stability. As the road erodes, the drainage capacity of ditches and culverts can be reduced, road banks undercut, and the road surface undermined. Such surface erosion can then lead to mass erosion (Carr 1983a). Skid roads also result in surface erosion, with poorly constructed skid roads producing 8 times the sediment of better-located skid roads (Jeffrey 1968).

Forest road construction is widely recognized as a major cause of mass wasting (Bourgeois 1978; Carr 1983a; Froehlich 1978; Rothacher 1970; Swanston and Swanson 1976). Initial road construction can modify a slope, and mass wasting from initial construction can occur over several decades (Froehlich 1978). Mass wasting is accentuated in steep terrain (Rice *et al.* 1985; Rothacher 1970; Swanston and Swanson 1976). Carr (1983a) cited a number of studies which indicated that road construction was responsible for 60-90% of all mass failures in managed forest land. Such landslides can begin in road fill or sidecast materials. Sediment stored in stream channels can also be removed during a mass erosion event.

Use of clearcut logging systems also leads to both surface and mass erosion. Poulin (1983) states that both provincial and federal agencies have acknowledged that current timber harvest practices can and do accelerate landslides in marginally stable terrain, where much of British Columbia's remaining timber supplies are found. Erosion problems from harvest practices are more severe on steep terrain (Rice *et al.* 1985).

Logging-related soil erosion has costly short- and long-term effects. Failed roads must be reconstructed. Soil erosion means that nutrient-rich, fine-textured soil is moved from the original forested site, often seriously altering the moisture and nutrient balance of the site and affecting future forest productivity (Fredricksen and Harr 1979; Ballard 1983; Froehlich and McNabb 1984). Mass wasting results in an initial destruction of most vegetation, creation of shallow soils, increased bedrock exposure, and conditions conducive to ongoing soil erosion (Smith *et al.* 1984).

Revegetation of landslide areas proceeds at a much slower rate compared to that on adjacent logged areas. Smith *et al.* (1983) recorded a 60% productivity loss for conifers in slide areas on the Queen Charlotte Islands. In addition, logging caused a distinct change in species mix, which was even more pronounced on landslide areas. The mineral soil exposed by mass wasting favored the establishment of red alder. Thus, Smith's study indicates that mass wasting may lead to vegetative successional changes which slow establishment of conifers. Landslides on forest land in western Oregon caused a 62% reduction in Douglas-fir height growth compared to that on clearcut areas, and the average stocking level was 25% less than the clearcut level (Miles *et al.* 1984).

In addition to the direct damage to forest productivity, erosion also causes other environmental problems. Sediment produced by erosion can enter stream systems and cause damage to domestic and agricultural water supplies, fish habitat, and fish populations. Mass wasting is a chronic source of sediment and debris entering productive salmon and steelhead streams on the Queen Charlotte Islands (Poulin 1983). The greatest impact of timber harvesting on water is through sediment production during and following road construction (Dyrness 1967; Fredriksen 1970; Swanston and Swanson 1976).

Fresh water is becoming a scarce resource in various parts of British Columbia, and water users are no longer willing to accommodate unnecessary soil erosion. Fisheries habitat managers are becoming less willing to compromise on soil erosion issues. Throughout British Columbia many of the remaining timber supplies are found on erosion prone and marginally stable terrain. Forest managers are now expected to reduce the occurrence of damaging soil erosion in order to protect other resource values.

2.2 Compaction

Detrimental compaction of forest soils is usually caused in harvest operations by the passage of machinery and their loads over skid roads and landings. Since most compaction occurs with only a few passes of a machine, compaction of lightly used skid roads is similar to that of heavily used skid roads (Schwab 1978; Froehlich *et al.* 1983). The effects of soil compaction have been shown to persist for several decades on many forest sites (Schwab and Watt 1981; Froehlich and McNabb 1984). Current logging operations in British Columbia compact large areas in the course of operations. In the Prince Rupert District, Schwab (1978) documented the percentage of area in skid roads to be 21-71%, depending on the type of machinery used.

Compaction can adversely affect tree growth. On compacted skid roads, 32-year-old trees were observed to have 30% less height growth and 55% less volume growth than trees growing on uncompacted ground (Froehlich and McNabb 1984). Poor height and volume growth are known to result from the effects of compaction on the tree root system that may include complex interactions between soil strength, water and nutrient availability, aeration, and mycorrhizal populations (Froehlich and McNabb 1984; Perry *et al.* 1984). Compaction also is known to reduce the infiltration capability of the soil, resulting in ponding or erosion (Sidle and Orlica 1981). Normal downslope movement of soil water and nutrients is interrupted, rendering portions of the site wetter or drier. Since severe compaction can have long-term adverse effects on forest productivity, less area compacted by skid roads and landings means less area lost to forest production.

In summary, surface erosion, mass erosion and compaction can have long-term adverse effects on future forest productivity: reduced availability of water and nutrients, decreased tree height and volume, reduced stocking levels, delays in seedling establishment, and establishment of brush species such as red alder. In addition, erosion from forestry activities causes increased sedimentation in streams, affecting water supplies and fish production.

3 CONSIDERING VALUES OTHER THAN TIMBER

From the preceding discussion it is obvious that soil degradation should be of direct concern to the forest manager because of the potentially substantial loss of future economic returns from timber harvest. However, as forestry operations conflict more frequently with other resource values such as water production and quality, fisheries, aesthetics, and wildlife, managers must also appraise these values when considering forestry operations in sensitive areas. The majority of foresters consider themselves to be managers of timber and have frequently thought little about the importance of other resource values or of how timber extraction might affect these other values. Corporate spokespersons frequently justify the quick economic return from timber production and its generation of jobs as sufficient reason for the pre-eminence of logging. The large, immediate dollar returns from timber extraction are highly visible. Values from other resources are either of lower immediate dollar value or are difficult to assess in monetary terms. The timber manager is therefore in a favorable position when arguing with proponents of other resource uses (Jeffrey 1968). However, water users, fisheries and wildlife personnel, native people, and environmentalists have been very successful in bringing their concerns about current timber management practices to the attention of the public. As public awareness increases, so does the amount of information available concerning costs and values of other resource uses. No longer can the forest manager truthfully state that timber extraction is always the most valuable use of forested land, even if only dollar values are considered.

Foresters must begin to recognize the long-term value of avoiding serious soil degradation by realistically considering the worth of other resource uses. Immediate dollar returns from timber extraction must be balanced with short-and long-term values of forest land uses such as fisheries and water production. When planning logging in watersheds, managers need to consider the value of that water for domestic and agricultural purposes and must recognize the cost to replace an equivalent system if logging damages that water supply. Logging-induced sedimentation of fish streams can seriously alter the number of fish fry (Everest 1978; Bustard 1983; Poulin 1983). In many instances rehabilitation of damage to water resources is prohibitively expensive or even impossible.

When all resource values are being considered, an honest evaluation of the economics of timber extraction is required. That this is not always the case, as stated by Krutilla and Fisher (1975):

> Many of the resource exploitation proposals that are undertaken are inherently uneconomic judged by established efficiency criteria, but may be privately profitable because of governmental policies favoring exploitation. Under strict efficiency criteria, these activities modifying the natural environment would not be undertaken whether or not there were adverse environmental side effects (p. 16).

Krutilla also points out that a biased benefit-cost comparison for resource development projects favors resource extraction industries. Such practices require the general public ultimately to defray the costs of such activities. As Brown (1984) states, "Only when economic value measures are placed in perspective do their nature and shortcomings come clearly to light" (p. 231).

Consideration of social values as well as of the dollar return from timber extracted is a responsibility of forest managers. A more approach to decision-making is needed so that timber, minerals, soils, water, fish, wildlife, and recreation resources, as well as social, political, and economic factors associated with these resources, are considered together (Everest 1978). Even where managers cannot attach monetary values, subjective weights assigned to the consequences of a choice will lead to improved decisions (Rice *et al.* 1985). If we encourage managers to use common sense with a more holistic view of the resource or resources they are managing, problems may be avoided (Pearce 1984). Avoiding costly soil degradation is an important aspect of a holistic view to forest management which will ensure sustainable timber supplies and protect other forest values.

4 COSTS OF SOIL DEGRADATION

The adverse effects of soil degradation all have dollar or social costs. Managers should not underestimate the combined total of the present and future costs of degradation. For example lost employment, decreased tax bases, lost investment opportunities, and relocation are future costs associated with decreased timber supplies. While many future costs cannot be stated in dollar terms, they constitute significant social costs.

Direct costs of mass and surface erosion and compaction at the expense of site productivity can be considerable. As has already been pointed out, most mass wasting in managed forests can be attributed to the construction of main access roads. Reconstruction of failed roads can cost 1.9 times as much as original construction (Bourgeois 1978), and repeated road failures will have a cumulative cost effect. In addition to the direct cost of reconstructing the road, other effects of mass wasting are also costly to rehabilitate. A 60% productivity loss for conifers in slide areas is costly in terms of lost volume on the next rotation. Restocking of one-third of the landslide area is likely to be unsuccessful due to unstable or impenetrable substrate (Miles *et al.* 1984). If red alder colonizes a coastal landslide area, there will be either a cost to establish conifers or a cost for lost productivity if no management occurs. Surface erosion from main and skid roads, and from clearcut areas, can result in the loss of soil and nutrients from a site. Again the cost will be either in reduced height and volume growth during the next rotation or the expense of fertilizer applications to attain desired yields.

The costliness of compacted soils is also high. Since the compaction of skid roads can last for decades, the site may have reduced productivity for that period of time. Reduced productivity on up to 70% of the land base (Schwab 1978) is very costly. Tillage of compacted skid roads may be effective in reversing the effects of compaction on productivity. Deep tillage is, however, estimated to cost $110/ha of skid road area (1982 U.S. dollars). Move-in, supervision, and delay costs must be added to this figure (Froehlich and McNabb 1984). Not all compacted soils will necessarily benefit from tillage. Even the best tillage is unlikely to return a compacted soil to its original condition and productivity (Andrus and Froehlich 1983). Rehabilitation of skid roads is bound to be costly and its effectiveness has not been adequately demonstrated (Smith and Wass 1985).

Hammond[1] estimated costs for rehabilitation of degraded forest soils to be between $2500 and $4000/ha in areas where soil disturbance levels ranged from 24.2% to 74.7% of the area. Forest soils ranged from fine-textured silty clays to coarse-textured loamy sands. Degradation included total to partial surface soil removal, burying of surface soil horizons, and compaction. Removal of surface soil was found to be more common on coarse-textured soils, while compaction was more evident on finer textured soils.

Cost estimates varied with the type and number of treatments required. Certain treatments were predicted to require repetition to be effective. In all cases, the objectives of rehabilitation were to facilitate the return of the site to its original level of productivity and to regenerate the area with seral conifers. Rehabilitation treatments included:

	Range of costs/ha
- re-establishment of normal site drainage patterns	$200 - 800
- stabilization of unstable sites	200 - 800
- reduction of compaction	100 - 200
- revegetation with appropriate shrubs and herbs (includes costs of seed collection and growing seedlings)	800 - 1100
- revegetation with appropriate seral conifers (includes costs of growing seedlings)	800 - 1100

Although comprehensive rehabilitation is expensive, concerted efforts must be made to correct existing soil degradation problems, especially since such problems frequently exist on the most productive forest sites in British Columbia. Currently there is a lack of political will to commit financial resources for adequately rehabilitating past and current problems, to incorporate planning and operations procedures that will avoid soil degradation, and to include rehabilitation and reforestation costs as a cost of doing business. A significant change of policy is required if past rehabilitation problems are to be corrected and future problems minimized.

Where soil degradation is severe, rehabilitation only hastens successional development of soils. In these instances, rehabilitated soils may show a decline in forest productivity in the limited time-frame of the next rotation period.

Data do not exist for volume losses resulting from trees growing on degraded soils throughout a rotation period. Volume losses of 55% have been recorded for 32-year-old trees (Froehlich and McNabb 1984). For purposes of illustration, a hypothesis of a 20% volume loss throughout a rotation period is used. A gross volume of 500 m^3/ha can be expected in medium quality coastal sites and on medium to good quality interior sites in British Columbia. Reducing an expected volume of 500 m^3/ha by 20% results in a volume loss of 100m^3/ha. Using an average price of $49.24/$m^3$ of logs (1985 Canadian dollars),[2] approximately $492/ha would be lost due to volume reductions on degraded land.

The economic and social costs of the effects of soil degradation on water supply and quality may far exceed the costs to forest productivity. Both commercial fisheries and agriculture rely on a consistent, high quality water supply in order to be viable. The economic return from a fishery or agricultural operation dependent on a particular stream may be comparable to, or exceed, the return from timber extraction. The economic advantage of fisheries and agriculture is that revenues are derived from an area annually. Periodic returns (every 50-100 years) from timber extracted on a specific unit of forest land may not equal the annual agricultural or fisheries revenues, over the same time-frame, that depend upon the maintenance of water quality. Therefore, the value of fisheries, agriculture, and domestic water uses must be considered by forest managers planning operations in watersheds. Destruction of fish habitat through sedimentation is extremely costly to rehabilitate. Frequently the damage is not reversible (Bustard 1983). All literature examined stated that prevention of damage to fish habitat is far more cost effective than rehabilitation of damage caused by sedimentation (Jeffrey 1968; Rothacher 1970; Everest 1978; Bustard 1983; Ryder 1983).

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[1] Hammond, H.L. Technical evaluation of forest management practices in the Nass River Valley. Report to the Nishga Tribal Council, March 1985.

[2] Average selling price of logs, all species, all grades. Council of Forest Industries, Vancouver, B.C.

Domestic and agricultural water users have frequently spent large sums to install their water delivery systems. If these systems are damaged or destroyed by sedimentation, the cost to repair or replace them can soon become prohibitive. For example, the District of Salmon Arm receives approximately 50% of its water supply via a gravity feed system from East Canoe Creek.[3] The remaining 50% of the water supply is pumped from Shuswap Lake. Sale of water from the gravity feed system generates between $200 000 and $250 000 annually. Use of the gravity system saves Salmon Arm between $65 000 and $75 000/yr in power costs over having to pump the water. If sedimentation were to render the creek water supply unusable, all of the district's water would have to be pumped from the lake. The estimated cost to expand the lake pump system would be in excess of $10 million. District annual operating costs, in terms of increased power expenses for pumps, must also be considered. The District of Salmon Arm is reluctant to permit logging in its watershed because of its experience with sedimentation problems which occurred during 1968-1972 from mass wasting of main forest roads constructed in the early 1960's. In 1985, a demonstration forest was established by the Ministry of Forests with two clearcut blocks of 16 and 80 acres. The effects of logging on water quality will be carefully monitored by a management committee of representatives from the Ministry of Forests and Lands, District of Salmon Arm, forest industry, and local ski club. No further logging will be permitted until results of current logging are evaluated.

Under current Ministry of Forests and Lands policy in British Columbia, the water user is liable for any damage occurring to its water supply. Conflict often results when timber extraction activities are proposed for domestic and agricultural watersheds. Given the lack of liability protection for water users, forest managers have a social responsibility to prevent the harmful sedimentation of water sources through timber extraction activities. The Salmon Arm example points out the economic benefits of stream water to the district. Such benefits certainly have an economic value similar to that of the timber to be extracted. Although forest management decisions leading to degradation of water supplies may have long-term effects on a large number of people, such effects are often not experienced by those making the management decisions.

5 PLANNING TO AVOID COSTLY REHABILITATION

The cost of rehabilitating the effects of soil degradation on forest productivity and the quality of water supplies is extremely high. Reconstruction of forest roads destroyed through mass movement of soil or surficial deposits is expensive. Yet forest managers in the past have stated that the cost of preventing degradation is not economically feasible. However, rarely have these managers been comparing the increased costs of prevention with the prohibitive costs of rehabilitation or reconstruction of roads. Rehabilitation costs were something that could be avoided or postponed. Responsible managers can no longer avoid the reality of rehabilitation costs and must realistically weigh the costs of prevention with the costs of rehabilitation (Carr 1983b). Again, the literature is unanimous in stating that the prevention of degradation is less costly than rehabilitation (Jeffrey 1968; Krutilla and Fisher 1975; FERIC 1980; Bustard 1983; Ryder 1983; Smith and Wass 1985).

Effective planning which considers all resource uses (timber, water, fish, wildlife, recreation) is the primary tool for the prevention of soil degradation (Bourgeois 1978; Everest 1978; Hammond 1984, 1986). Planning can most effectively prevent soil degradation when large drainage basins, or watershed units, are planned because management activities affect soil and sediment routing on this scale (Cromack *et al.* 1978; Jakoy 1983). By planning development activities in watershed units, the chance of soil degradation can be reduced through the minimization of the length of main and spur roads constructed.

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[3] Personal communication, Mr. Don Huntington, Superintendent of Public Works, District of Salmon Arm, B.C., February 10, 1986.

Effective planning processes will include a variety of components. Some form of site classification to determine risk analysis is essential (Rice *et al.* 1985). Use of a terrain stability rating system will assist in preventing potential degradation. Terrain stability is based on landform type, material textures, slope gradient, uniformity of slope, length of slope, soil types, soil moisture regime, underlying bedrock type (Bourgeois 1978; Hammond 1984). By avoiding unstable sites or routes, and by making an informed choice of location, a planner can minimize the potential for future problems and avoid unnecessary costs (FERIC 1980). Overall planning should consider future forest management objectives when permanent road locations are being selected, not just the present extraction of timber (Jakoy 1983).

Specific road construction techniques which will minimize soil degradation include: full benching of roads on steep terrain; matching the machine to the terrain to reduce constructon costs and potential stream sedimentation; and installation and maintenance of a good drainage system to minimize road failures (Bourgeois 1978). Conscientious, complete field reconnaissance is critical at all levels of route selection (Jakoy 1983; Hammond 1984).

Identification of unstable terrain also permits managers to predict the probability of a slide after clearcutting. Forest managers can attempt to estimate the risk of landslides and to effect an appropriate balance between timber utilization and hazard to soil and water (Rice *et al.* 1985).

Planning at all levels must include analysis in the field in order to be effective. Field-based planning will ensure the best use of the available forest resources and will result in the most accurate assessments and layouts. A planning system which can be upgraded efficiently from broad to specific levels will be the most cost effective (Hammond 1986).

Compaction reduces site productivity over several decades and is costly to rehabilitate. Reduction of the amount of area degraded by compaction is therefore a prime objective (Smith and Wass 1985). The most efficient and cost-effective method of preventing compaction is the use of pre-planned, designated skid roads (Froehlich *et al.* 1981; Froehlich and McNabb 1984; Olsen and Seifert 1984). Reducing skid road width and density will correspondingly reduce losses in growth potential on the site (Smith and Wass 1979). Pre-planned skid roads can economically be held to about 10% of the harvest area (Froehlich 1978). The efficiency and cost-effectiveness of designated skid roads are increased if trees are felled to the lead of the skid road (Froehlich *et al.* 1981).

Planning costs are usually expressed per unit of timber volume harvested rather than per unit of area planned. Planning costs for areas with higher volumes of timber per unit area will therefore be proportionately less than for equal areas with lower timber volumes. However, writing off planning costs against timber volumes does not accurately reflect planning benefits to forest land planned but not harvested. Such land may be harvested in the future or protected from timber harvest due to other land use considerations. Converting planning costs from per unit of timber volume harvested to planning costs per unit of forest area shows an approximate range of $200-405/ha (Hammond and Ingram 1985). These planning costs include several entries to a site to carry out reconnaissance, improve data resolution, design and lay out operations, an devaluate results. Standard forest assessments such as cruising, silvicultural surveys, preliminary road locations, and harvest unit design are a part of these planning cost estimates. Planning costs as low as $50/ha may be anticipated in large planning units in which ecosystems are not complex and design and layout criteria are straightforward.

Planning should also consider the importance of training all personnel,including engineers, foresters, biologists, and operators. A training program is essential if the management decisions are to be carried out efficiently and cost effectively (Bourgeois 1978). The best planning possible will be useless if personnel are incapable of effectively carrying out the prescriptions. Individual operators can significantly affect logging cost and damage to the site. Operator performance may be as great a source of variation in logging-related erosion as are site characteristics (Rice and Datzman 1981). While training will initially be costly, the amount saved over the long term in increased efficiency and decreased rehabilitation costs will exceed the initial training costs.

Effective planning can drastically reduce both short- and long-term costs by avoiding soil degradation and the subsequent rehabilitation. Such planning, which includes the consideration of all resource values, avoids far more costs than it incurs. A case can be made for managing forested areas for water quality. Often water quality considerations are also economic in terms of maintaining site quality, minimizing road mileage and maintenance, and reducing treatment costs (Rothacher 1970). In any event, the planning objectives for both economic timber harvest and environmental concerns are compatible. The same level of planning that reduces the need for road and site rehabilitation also reduces the incidence of sedimentation damage to streams. Thus, avoiding environmental degradation through effective planning is not more costly.

6 CONCLUSION

Forest management activities can cause long-term soil degradation which is costly to rehabilitate. Road failures are expensive to correct and may cause extensive environmental damage to streams. Mass and surface erosion resulting from road construction and clearcut logging practices generally reduce forest site productivity in the next rotation. Compaction resulting from excessive skid road construction and use may last for several decades. Environmental damage from erosion includes sedimentation of streams, which damages fish and wildlife habitat and domestic and agricultural water supplies. All of these adverse effects are costly to rehabilitate, and often rehabilitation is not possible.

Forest managers have an obligation to consider other resource values when planning timber extraction, especially when other uses are already well established in an area. The economic returns from timber extraction do not justify the costs of degradation of fish habitat and existing domestic and agricultural water supplies.

Effective planning of all resource uses at a watershed level is a cost-efficient means of avoiding the loss of productive forest land and damage to streams. Planning will include analysis of terrain stability to avoid road construction and logging activity on unstable sites; road design, layout, construction, and maintenance standards that will reduce the chance of erosion; designation of skid roads to reduce compaction; and field layout of planning at all stages. Training of all personnel is essential to the success of operations in avoiding soil degradation.

Forest managers must be certain that planning includes an accurate evaluation of costs and benefits to be derived from timber extraction and other resource uses. With this approach, costly rehabilitation and permanent damage to forest ecosystems can be avoided. Quality of environment should be viewed as a basic right of all living organisms. Managers must be careful that their desire for short-term economic advantage does not jeopardize future timber supplies and the long-term, socially desirable environmental base.

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________. 1984. Vegetative succession, soil development and forest productivity on landslides, Queen Charlotte Islands, British Columbia, Canada. *In* Proc. IUFRO Symp. on Effects of Forest Land Use on Erosion and Slope Stability. Honolulu, HI, pp. 109-116.

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SESSION 6

Research Needs

Session Chairman:
J.D. Lousier
Ecology Program
Research Branch
B.C. Ministry of Forests and Lands
Victoria

SESSION 6 RESEARCH NEEDS

ROCKS ON STUMPS: THE IMPORTANCE OF PAST RESEARCH SITES AND MICRO-PLOTS FOR SITE DEGRADATION STUDIES

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ABSTRACT

Presentations at this workshop have revealed the serious need for long-term study on the effects of current forest management practices and policies on forest soil degradation. However, most research to address long-term effects is of recent initiative; in the interim, valuable information may be provided by past research and trial areas. Resampling past studies provides feedback for current forest management decisions and insight for current research (although past data sets require some special considerations). Past research sites enable current researchers to expand the scope of their efforts by increasing the range of time-since-treatment and site conditions. The 43-year-old research sites of Mr. Tom Wright provide a good example of one kind of past research that can now provide many years cumulative feedback for slashburning decision-making and research techniques, and on data types (e.g., long-term usefulness of mineral soil exposure data). The examples attest to the advantages of using "micro-plots", within research and trial areas, for monitoring possible site degradation. Micro-plots provide large, paired-data sets for sensitive within-site evaluation of long-term relationships of tree performance with management impacts. Mr. Wright's plots also demonstrate the importance of thorough documentation of research methods and efforts to enable any follow-up study. Documentation of many current research and trial projects (including data, locational, and photographic records) should be improved. Materials used for permanent plot markings should be evaluated for durability. (Mr. Wright used rocks on stumps and railroad spikes.) The advantages of the micro-plot approach are clear, and we can benefit by exploiting old research sites for new studies.

1 INTRODUCTION

Since forest management first began in British Columbia there have been interest and argument regarding the effects of management practices and policies on the maintenance of long-term forest productivity. This workshop has revealed that there still is a serious need for long-term study of the effects of current forest management practices and policies on forest land degradation. Clearly, a number of these issues have not really changed (e.g., Wright 1941) and still go unresolved; much research is still of a relatively short-term nature. Short-term study of long-term effects is difficult because of the length of forest rotations. The establishment of long-term studies that can eventually answer long-term questions has, until recently, been rare for most aspects of forest soil degradation. Clearly, until information comes onstream from these new studies, foresters will be hard-pressed to make informed decisions to prevent site degradation. Even with the knowledge gained from the new studies, questions will remain regarding the effects on site conditions other than those studied and the implications for longer time periods (e.g., complete rotations). Study of past research sites can fill these information gaps.

During a number of past studies, researchers have taken care to make adequate records and, in some cases, make adequate markings on the ground to enable follow-up study. These old research plots provide unique opportunities for studies on the long-term implications of past forest management practices (most of which are similar today). Thus, some feedback on management practices may be provided now; this will aid forest management in the interim and provide insight for new research (e.g., usefulness of certain measurements, plot marking techniques, etc.). However, even in the future, past research sites will always prove valuable in augmenting new research findings by increasing the range of site conditions and time-since-treatment that can be considered when evaluating possible site degradation. (If you know of any past or existing research sites, please consider their future.)

Some past research studies attest to the importance of using "micro-plots," within research and trial areas, for monitoring possible site degradation (e.g., for slashburning: Wright 1942;[1] Lafferty 1972; Muraro *et al.* 1973; King and Oswald 1982). Hawkes (in press) defines micro-plots as small plots approximately less than 15 m^2 in size; in my work on past research areas these have ranged from 4 m^2 to 40.5 m^2 in size, and from 9 to over 30 in number per treatment area. Micro-plots increase the sensitivity of site degradation studies by facilitating within-site analyses that are vital in resolving relationships (because site conditions, regeneration and treatment impacts vary substantially within-site).

A rock on a stump is a monument to mark something on the ground (e.g., a research plot from the past). The title for this paper was inspired by the past research of Mr. Thomas G. Wright (Wright 1941, 1942,[2] 1943). The paper builds on examples set by Mr. Wright over 40 years ago and draws on other slashburning examples from the author's current research. (Much of what is said and concluded can be applied to almost any aspect of research into forest soil degradation).

This paper focuses on three key points:

1. the importance and limitations of resampling past research plots to gain feedback for current forest management and policy formulation, and current research,
2. the use of "micro-plots" to evaluate possible site degradation within individual treatment areas, and
3. the importance of thorough research documentation and plot marking.

2 IMPORTANCE AND LIMITATIONS OF PAST RESEARCH AND TRIAL AREAS

Past research and trial areas of interest in the study of long-term forest management effects on tree growth and site nutrient status include those areas with good location and site documentation that (1) have detailed documentation of treatment impact and/or (2) are of historical or unique value. Past prescribed fire research areas currently being studied by the author in coastal British Columbia range from areas where adjacent burned and unburned sites exist (e.g., sites used by Knight [1964] and Vihnanek [1985]) to sites where detailed fire impact monitoring was related to many transferable points on the ground (e.g., sites from past CFS studies at Mission Tree Farm (Lafferty 1972) and Pacific Rim National Park (Muraro *et al.* 1973)). Of great interest to the study of long-term effects have been the sites of Wright,[3] which provide an example of past research that now provides unique opportunities for follow-up study.

2.1 Franklin River Sites Established by Mr. T.G. Wright

In 1941, Mr. Wright, then an Assistant Professor in Forestry at the University of British Columbia, approached Mr. Sid Smith of Bloedel, Stewart and Welch Limited, for summer employment as a chokerman, to gain experience in British Columbia forestry practices. However, Mr. Smith hired Mr. Wright to prepare a report on the state of the company's forest lands; Mr. Smith was particularly concerned about a large tract of land in the Franklin River Valley that the B.C. Forest Service had instructed them to slashburn in 1938 (the dry summer of the devastating Bloedel Fire in the Sayward Forest on Northern Vancouver Island). As probably the first consulting forester in British Columbia ($6.00/day), Mr. Wright carried out a number of surveys and studies during the summers of 1941, 1942 and 1943, culminating in two reports (Wright 1941, 1943) (T.G. Wright, Consulting Forester, pers. comm., Vancouver, B.C.).

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[1] Wright, T.G. 1942. Fieldbook from permanent plots established in the Franklin River area on Vancouver Island. MacMillan Bloedel Limited and University of British Columbia.

[2] Ibid.

[3] Ibid.

In 1942, Mr. Wright established permanent sample plots on the severest south and west exposures in the 1938 slashburn. These areas still appeared very desolate (Fig. 1), although they are now well vegetated (Fig. 2). Mr. Charlie Dunham, the company engineer, had told Mr. Wright that the best way to mark an area for future reference was to simply put a rock on a stump. Mr. Wright took his advice to heart. Using railroad spikes as plots centers, Mr. Wright established 23 micro-plots off "Branch 16" and 15 off "Branch 17", and had an assistant establish 22 off "Branch 17A;" each had a bearing and distance from the nearest rock on a stump or rock cairn. These 11.78 ft (3.59 m) radius (10^{-2} acre, 4.05×10^{-2} ha) plots were established on a 100 ft (30.49 m) compass grid with a random start. All tree regeneration, surface cover, and slash was mapped for each micro-plot, with percent cover estimates recorded for the latter two and vegetation (Fig. 3). A key map illustrated the relationships of the plots to one another and to local geographic features (Fig. 4). A photo was taken of each plot, with the photo direction indicated on the plot map (e.g., Fig. 3) and an axe providing scale and marking the location of the railroad spike (Fig. 5). (Mr. Wright took at least 11 rolls of film during the summer of 1942.)

The Branch 16 and 17 plots were all successfully relocated in the summer of 1985, thanks to the rocks on stumps and the support of key individuals at MacMillan Bloedel Ltd. (Mr. Grant Ainscough, Chief Forester, preserved the original fieldbooks in his archives; Mr. Bill Beese, Research Ecologist, notified the author of the sites after being informed by Mr. Jack Dryburgh, Divisional Forester). The Branch 17A plots were successfully relocated in the summer of 1986. The original work appears to be very accurate and precise. (For interest, Fig. 6 is a 1950 photo of the same area and Fig. 7 is a 1985 photo; Figs. 8 and 9 are 1941 and 1985 photos of Mr. Wright, and Fig. 10 is of other past regeneration research.)

Mr. Wright was well ahead of his time; his work could put many of us current researchers to shame today. A number of fundamentals for good (and transferable) research documentation have stood the test of time in his work; we should strive to make these the common denominator in all current research.

2.2 Benefits and Limitations of Resampling Past Studies

A number of benefits are possible from resampling past research or trial areas (Table 1); these focus on the provision of feedback for (1) current forest management and policy formulation, and/or (2) current research efforts. In addition, resampling takes advantage of previous investments in initial project set-up and can increase the scope of existing research studies by enlarging the range of site conditions and times since treatment. In the slashburning example, sites being studied will allow feedback up to 47 years after treatment, for sites ranging from western Vancouver Island to Mission. At Mission Tree Farm, relationships apparent on 15-year-old CFS research plots are providing insight for current monitoring of a 1985 slashburn (Curran *et al.* 1986).

TABLE 1. Summary of advantages and limitations of resampling past research sites

Advantages:	**Limitations:**
- Feedback provided NOW for: Current management and policy Current research efforts	- Data set must be questioned: Measurements (before/after?) Methodology (documented?) Missing data (for new use)
- Capitalize on previous investments	Differing accuracy/precision Sampling design
- Increases scope of current studies Elapsed time since treatment Range of site conditions	- Controls may be lacking or non-representative

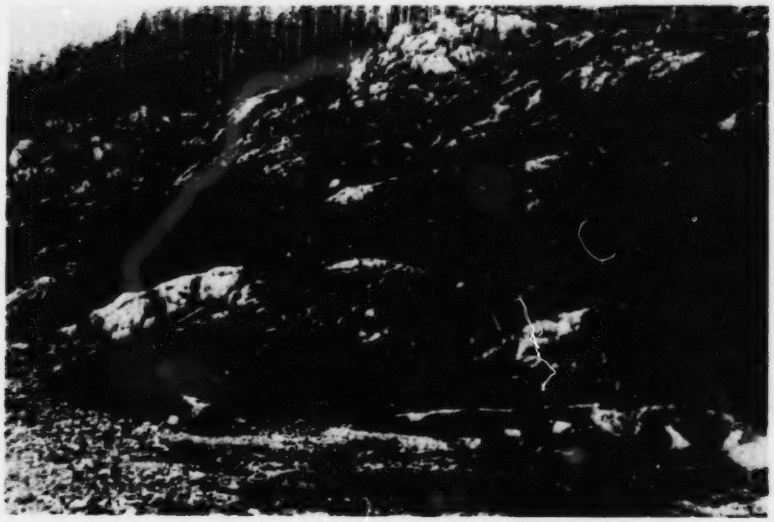


FIGURE 1. 1942 photo of Mr. Wright's study area from Branch 17 at Franklin River (burnt 1938).

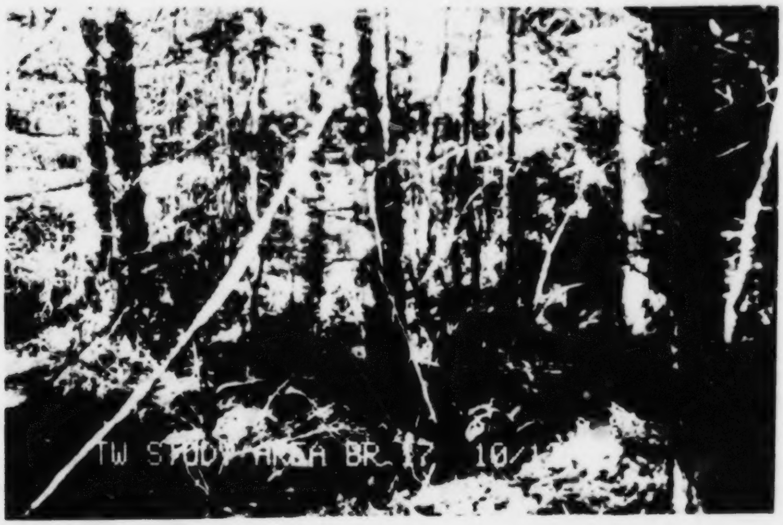

TW STUDY AREA BR 17 10/1

FIGURE 2. 1985 photo of Mr. Wright's study area from Branch 17.

BR. 16

PLOT 21

MAY 29, 1942

Exposure NW

Mineral soil	50%
Moss	30%
Duff	20%
Shade	2
Slope	15
Weeds:	
Fireweed	40
Bracken	40
Salal	
Willow	
Black ras.	

There is a much-used deer bed on this plot.

Note (1986)

L = Log

LX = Log in air

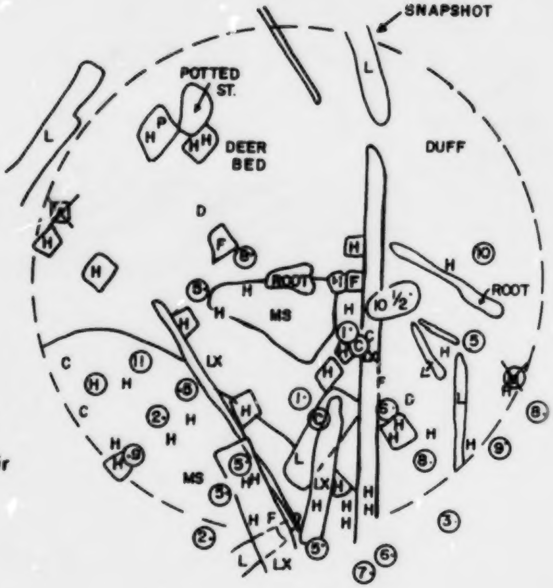
F = Douglas-fir

H = Hemlock

C = Cedar

MS = Min. soil

D = Duff


SNAPSHOT
POTTED ST.
DEER BED
DUFF
ROOT
ROOT
MS
MS
LX
LX
D
L
C
F
H

Center of plot – old wedge in root 15' N 10 W from stump

Snapshot — see arrow

FIGURE 3. Field book entry for Mr. Wright's plot 21 off Branch 16.

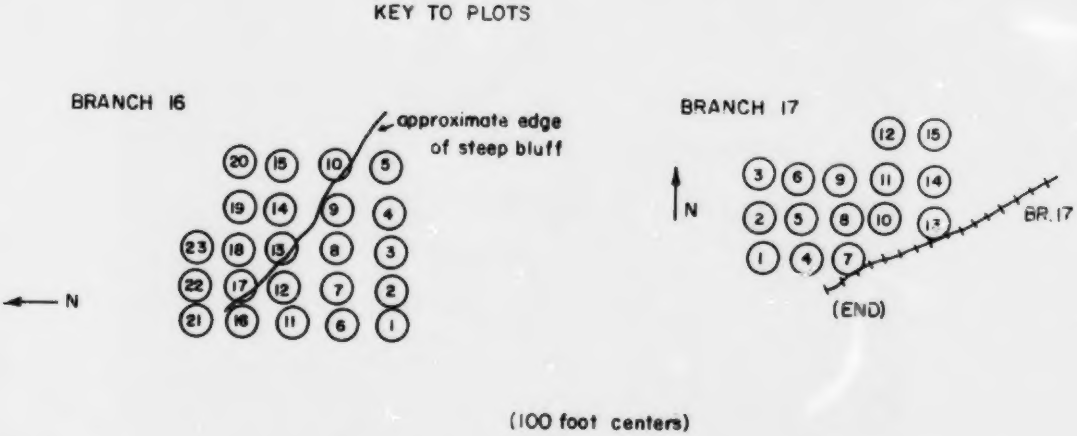

KEY TO PLOTS
BRANCH 16
approximate edge of steep bluff
N
BRANCH 17
N
BR. 17
(END)
(100 foot centers)

FIGURE 4. Key map for Mr. Wright's plots off Branch 16 and 17.

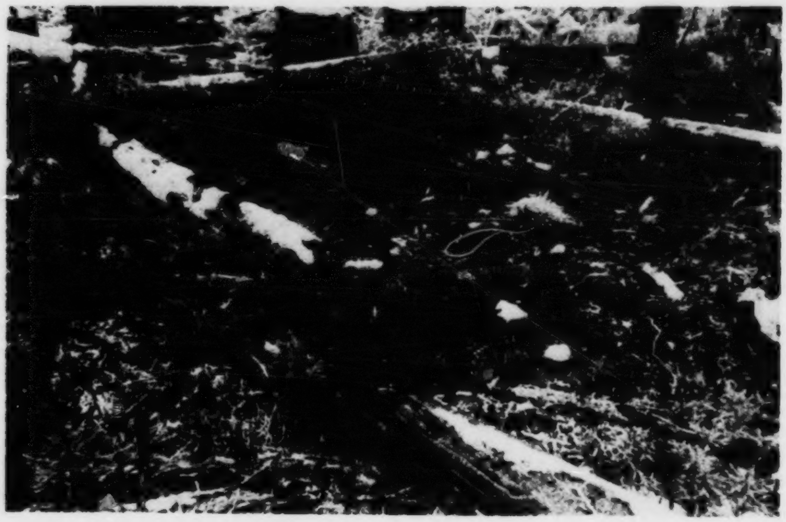


FIGURE 5. 1942 plot photo for Mr. Wright's plot 21 near Branch 16.

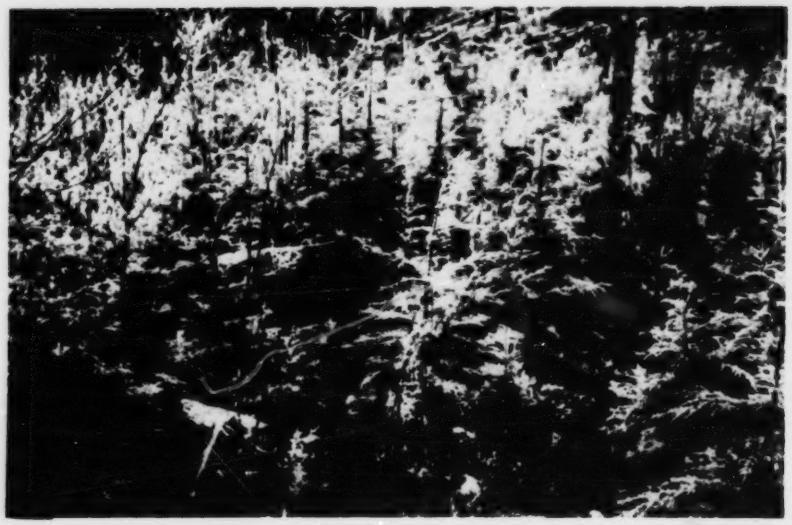


FIGURE 6. 1950 photo of Mr. Wright's plot 21 near Branch 16.

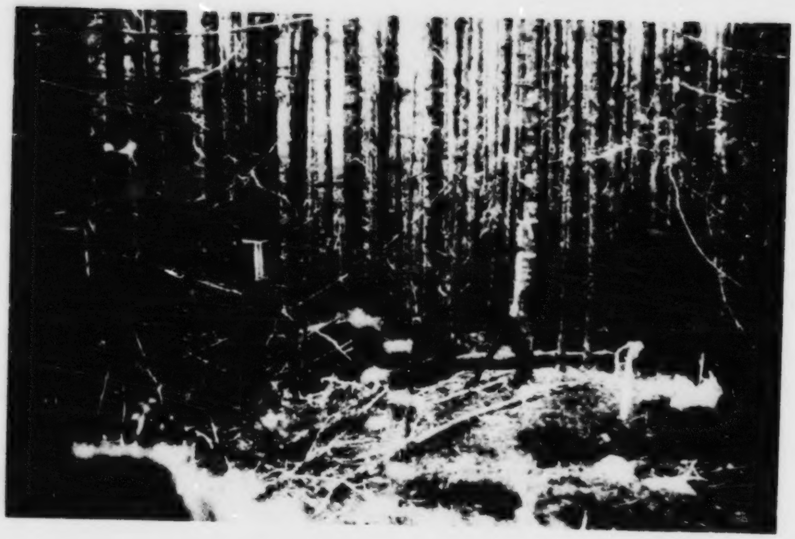


FIGURE 7. 1985 photo of Mr. Wright's plot 21 near Branch 16.

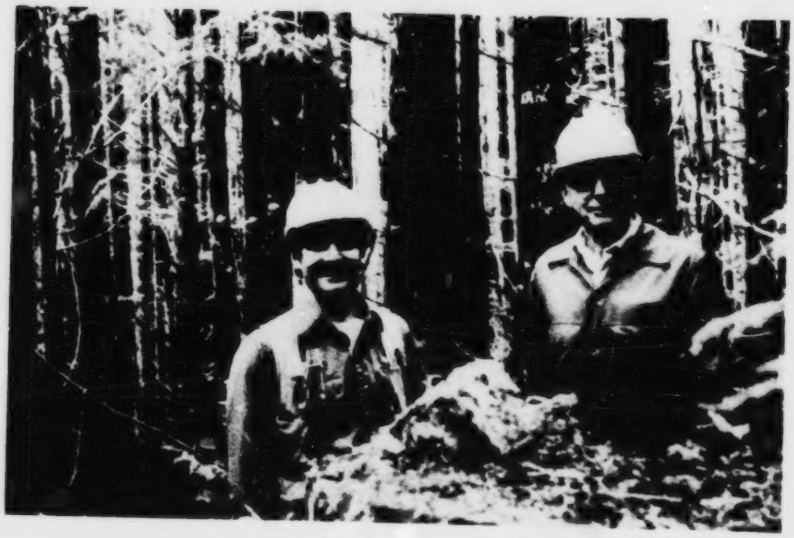


FIGURE 8. Mr. Wright and Bill Beese with one of the 'rocks on stumps'.

FIGURE 9. 1941 photo of Mr. Wright, the "stump counter", on one of his "reconnaissances" of the logged land.

FIGURE 10. 1941 photo of Mr. Larry MacMullan and co-worker, from the B.C. Forest Service, surveying one of their regeneration plots in the Port Alberni area.

In addition to their originally intended uses, past research sites can also offer a wealth of other information. For example, Mr. Wright's sites offer unique opportunities to study, among other things, forest stand development, forest floor development, and treatment effects on competing vegetation (Curran *et al.* 1986). Past research areas also provide opportunity for quick evaluation of initial hypotheses before large investments are undertaken. Some detailed studies from the more recent past may allow us to evaluate which impact and tree measures appear worthy of the most emphasis in a new research project. For example, on the Pacific Rim National Park sites, large fuel consumption figures prominently in preliminary results (Curran and Ballard 1986).

However, there are a number of limitations that must be considered in resampling past research sites (Table 1). Limitations focus on the nature of the data set from the past: pretreatment site conditions and the nature of the actual treatment may not be adequately recorded. (For example, for slashburning this includes Fire Weather Indices, weather during burn, fuel loading, initial mineral soil exposure, initial duff depths, light-up sequence, etc.) Documentation of actual impact may also be incomplete by today's standards, it may have been measured differently, and these methods and their relative accuracy and precision may not be apparent in existing documentation. Past research sites were often located in a non-random manner, through biased and/or systematic sampling designs. Depending on the statistical analyses planned, this may be an important consideration when resampling is being done. Control plots that were sampled or established may represent incidental, non-treated areas and/or different site conditions.

In summary, despite limitations, past research sites are worthy of consideration because of the importance of the long-term perspective provided for forest management impacts, and the experience from which current research efforts can benefit.

3 IMPORTANCE OF USING "MICRO-PLOTS" WITHIN TREATMENT PLOTS

An important message in Mr. Wright's research are the benefits of using micro-plots within each research area (e.g., 23 micro-plots off Branch 16). Micro-plots provide large data sets (e.g., Table 2) for more sensitive within-site analyses. This minimizes "noise" caused by variability in growth-determining factors, variability that must be accounted for when forest management practices are being monitored for possible site degradation. In slashburning studies, sources of spatial variability are: site conditions (including vegetation and soils), fuel loading, light-up sequence, and resulting fire behavior (e.g., coverage, and fuel and duff reduction). By having numerous data measures within each treatment (i.e., many micro-plots), this confounding variability problem may be minimized by pairing variation in tree growth and nutrient status with variation in impacts. Temporal variability sources are, primarily: plant succession (including stand development), and diurnal and seasonal fluctuations. By studying past research sites, a range of times-since-treatment may be sampled to provide insight into temporal variability. Treatment effects may reverse over time, relative to sites with less or no impact (Braathe 1974; Curran and Ballard 1985).

In contrast, analysis of plot averages is necessary in most past studies of the long-term effects of slashburning, because fire impact data for an individual tree micro-site are unknown in later years when the trees are re-measured. This limits data analysis because of the variability discussed above. The micro-plot approach is compared to the more common treatment average approach in Table 3. The latter method allows only one data point per treatment; because of this and within-plot variability, sensitivity is reduced and researchers are required to base their study results on comparisons with other sites. This introduces between-plot variability, which, combined with the fewer data points, may render relationships with treatment-impact hard to resolve or more obscure. On the other hand, if treatment-impact data exist for many micro-plots transferable within each treatment plot, sensitivity is substantially increased by the large paired-data sets. Tree performance data can, thus, be paired with within-site variation, and statistical evaluation of site degradation is possible within each treatment. All these advantages increase analytical sensitivity which allows a greater resolution of relationships.

TABLE 2. Examples of large data sets possible from use of micro-plots

Study Area[a]	No. Treatments	No. Micro-plots	Total Micro-plots
Mission TFL	4 (2)[b]	25	100
Pac. Rim Nat. Park	4 (1)	25	100
Carnation Ck.	4 (4)	variable	70
T. Wright's	3 (1)	15, 22 & 23	60
Totals	15 (8)		330

[a] Mission work based on Lafferty (1972) and funded by CFS, B.C. Ministry of Forests and Lands, MacMillan Bloedel Ltd. and B.C. Science Council. Pacific Rim work based on Muraro *et al.* (1973) and funded by CFS. Carnation Creek work based on King and Oswald (1982) and funded by B.C. Ministry of Forests and Lands. T. Wright work based on Wright (1942) and funded by B.C. Ministry of Forests and Lands, MacMillan Bloedel Ltd. and B.C. Science Council.

[b] Number of areas considered as controls are in parentheses, and not included in "Total Micro-plots".

TABLE 3. Comparison of micro-plot and treatment average approaches

Treatment Averages	Micro-plots
Sensitivity lost by averaging records	Sensitivity maintained with data
One data point for analysis - Limited data analysis	Many data points for analysis - Increased data analysis
Sensitivity within site lost	Sensitive to variation within site
Relationships only with other sites	Relationships can be resolved - Within site - Between and among sites

The use of micro-plots can, thus, provide very powerful data sets which allow one to evaluate possible site degradation on an individual treatment-area basis, and enable analysis of the variance within and between individual treatment areas. The costs involved in micro-plot sampling need not be exorbitant; for example, one approach may be to "break up" currently used large plots into smaller units of record that can be used in combination or alone. This combined approach might be desirable for fire researchers because micro-plots may not characterize impact over a large area any better than larger plots. (Despite the smaller sampling area of micro-plots, the two approaches can have similar coefficients of variation for duff reduction[4] and the micro-plot approach can result in higher standard errors for fuel consumption (Hawkes [in press]), presumably because the shorter transect length yields more extreme values). However, for site degradation studies, a primary concern must be the relating of observed impacts to tree performance on individual micro-plots. In fact, Hawkes' (in press) study suggests that micro-plot means for fire impact data may not usually be significantly different from large plot means (one exception in his study).

Since most advantages of micro-plots are based on exploiting paired-data sets, much information may be available regarding other aspects of site ecology. For example, data from my resampling of Mr. Wright's research areas are being used to study the relationships between treatment impacts and competing (and/or indicating) species, and between understory competition and crop tree performance. Methodology and further rationale for micro-plot sampling for prescribed fire research is discussed by Hawkes (1986); much of his discussion is of interest to other site degradation studies.

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[4] Feller, M.C. 1986. Small plot burns and the estimation of forest floor depth of burn caused by slashburning in coastal British Columbia forests. Unpubl. manuscript submitted to Can. J. For. Res.

4 DOCUMENTING RESEARCH PLOTS FOR LONG-TERM STUDY

4.1 File Documentation

Mr. Wright's study illustrates an example of proper documentation of research plot location and description for use in long-term studies. Although the approach and what is added here is largely common sense arising from field experience, it warrants discussion for completeness. The basic components for research documentation are (1) data records, (2) locational records, and (3) photo records (Table 4). Reports (progress and final) are also extremely important in integrating documentation and results, and it is recognized that the following discussion also applies to them. It is a good idea to make back-up copies of all of these records on a routine basis, storing the duplicates elsewhere or in a fire-proof location. For a number of us, the cost of widespread duplication of photographic records is prohibitive; this can be partly overcome by taking duplicate photos in the field, either routinely or for the most important scenes.

Some types of detail that should be documented may not be appropriate for detailed progress reports, but any follow-up work may be crippled without them. It does not take much extra time for proper study documentation, but few researchers do. Considering the nature and size of our research investments, we should be expending the necessary effort to ensure adequate and proper documentation.

TABLE 4. Some key features of well-documented research

Micro-plots are used (data records for individual points within setting)

Data Records:

- "Basic" data records
- Methods employed for impact monitoring and data collection are well documented
- Data records related to identifiable point on ground (numbered micro-plot)
- Research area related to current tools for communication (e.g., ecosystem classification system)

Location Information:

- Point (micro-plot) permanently marked on the ground with a numbered marker
- Map of microsite conditions of interest (including microsite numbering)
- Map showing location and spatial relationships of micro-plots (including numbering system)

Photographic Records:

- Permanent photo point marked or described
- Camera details (e.g., lens focal length)
- Item in photo for scale
- Photo inscribed with microsite number and date (etc.), using databack

Data record problems associated with a treatment plot average approach have already been discussed (e.g., Table 3); however, another common problem of a more specific nature is the recording of more "basic" data as opposed to more "interpretive" data. As used here, "basic data" describe actual feature properties; measuring residual duff depth in a slashburning study, for example, may involve recording the actual depth or depth classes of the latter (e.g., greater or less than 10 cm depth). We often neglect to record basic data because of real or perceived time and financial constraints. Interpretive data contain classes or interpretations of feature properties for which the sampler must first determine an approximation of the actual value; without recording this, much of our accountability is lost. Implicit in this approach, of course, is that data records are kept for all the micro-plots. Data records must also contain the details on actual methods employed in site establishment, site treatments and data collection.

Locational records include maps and field markings. It is desirable for all locational records to be kept with other records, to prevent possible misplacement in the future. Of vital importance is a master plan (e.g., Fig. 11) or sketch map with accompanying plot plans (e.g., Figs. 12 and 13) showing the location and numbers of all

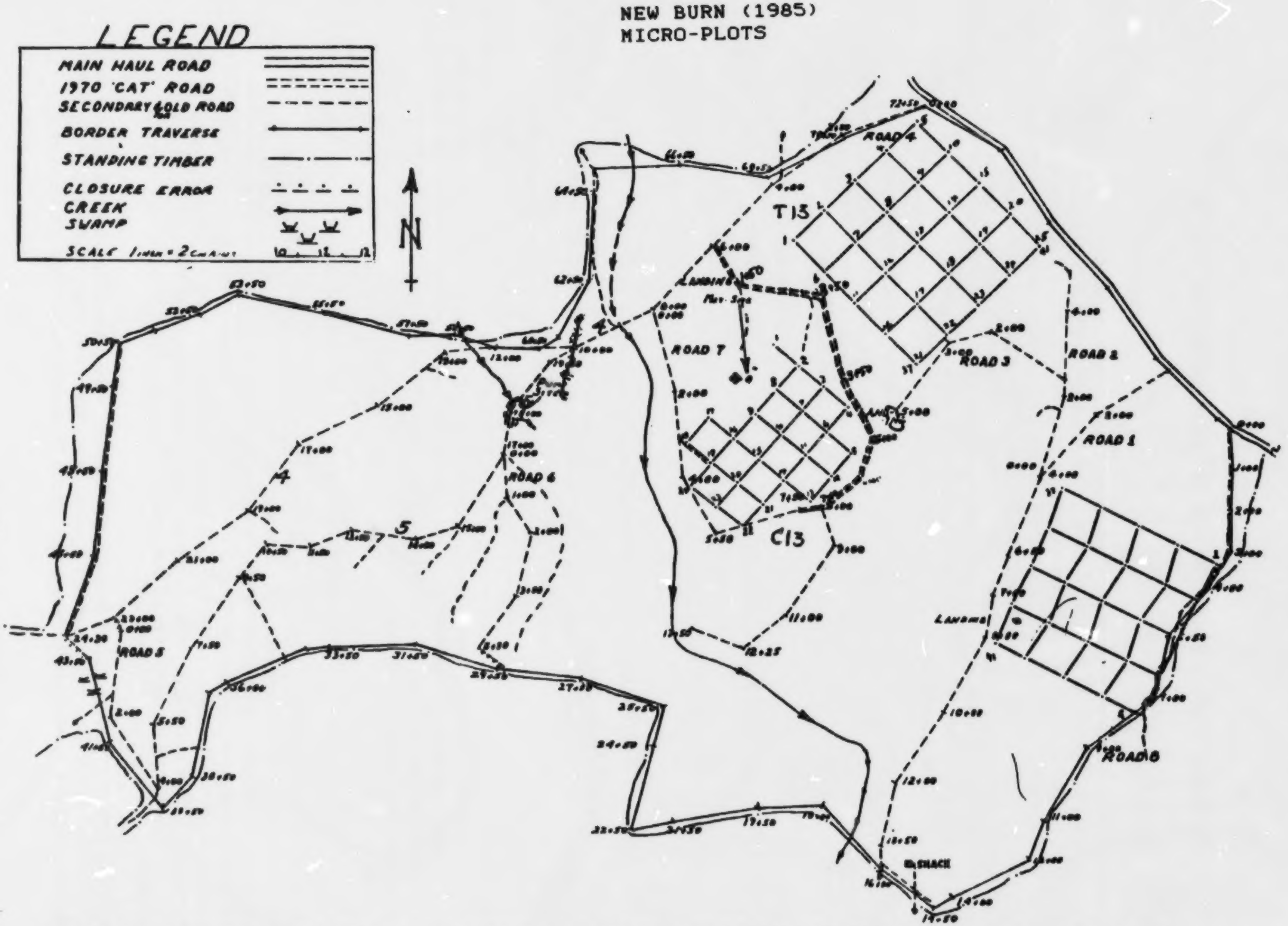
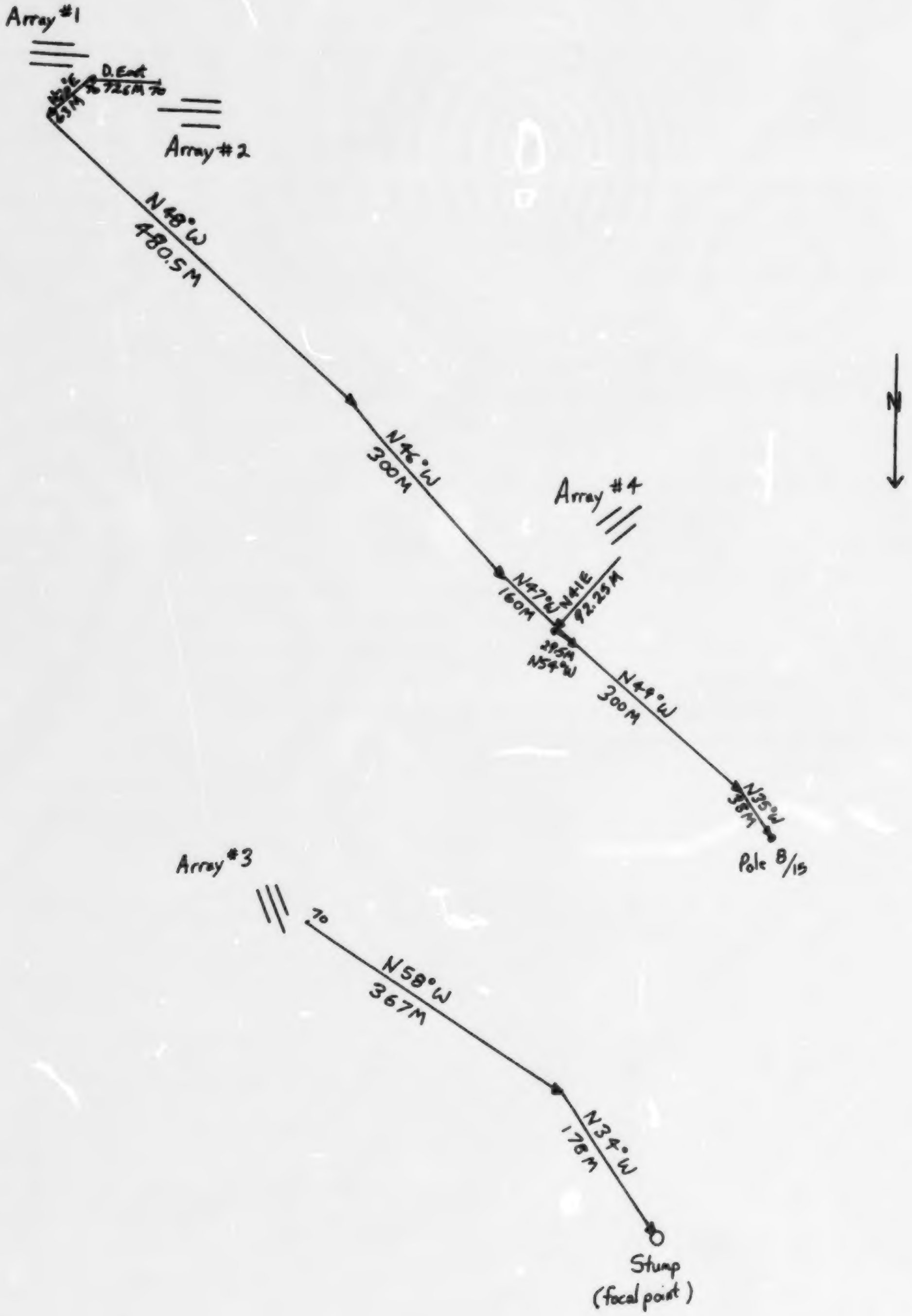

NEW BURN (1985)
MICRO-PLOTS
LEGEND
MAIN HAUL ROAD
1970 'CAT' ROAD
SECONDARY & OLD ROAD
BORDER TRAVERSE
STANDING TIMBER
CLOSURE ERROR
CREEK
SWAMP
SCALE 1 inch = 2 chains
N
T13
C13
ROAD 1
ROAD 2
ROAD 3
ROAD 4
ROAD 5
ROAD 6
ROAD 7
ROAD 8
LANDING
SHACK

FIGURE 11. Master plan for 1970 CFS fire research plots T13 and C13 at Mission Tree Farm (including location of burn monitored in 1985).


Array #1
D.Ent.
72.6M
70
Array #2
N48°W
480.5M
N45°W
300M
Array #4
N47°W
160M
N41E
92.25M
29.5M
N54°W
N49°W
300M
N35°W
38M
Pole 8/15
N
Array #3
70
N58°W
367M
N34°W
178M
Stump
(focal point)

[facsimile]

FIGURE 12. Sketch map showing location of 1971 CFS fire research plots at Pacific Rim National Park.

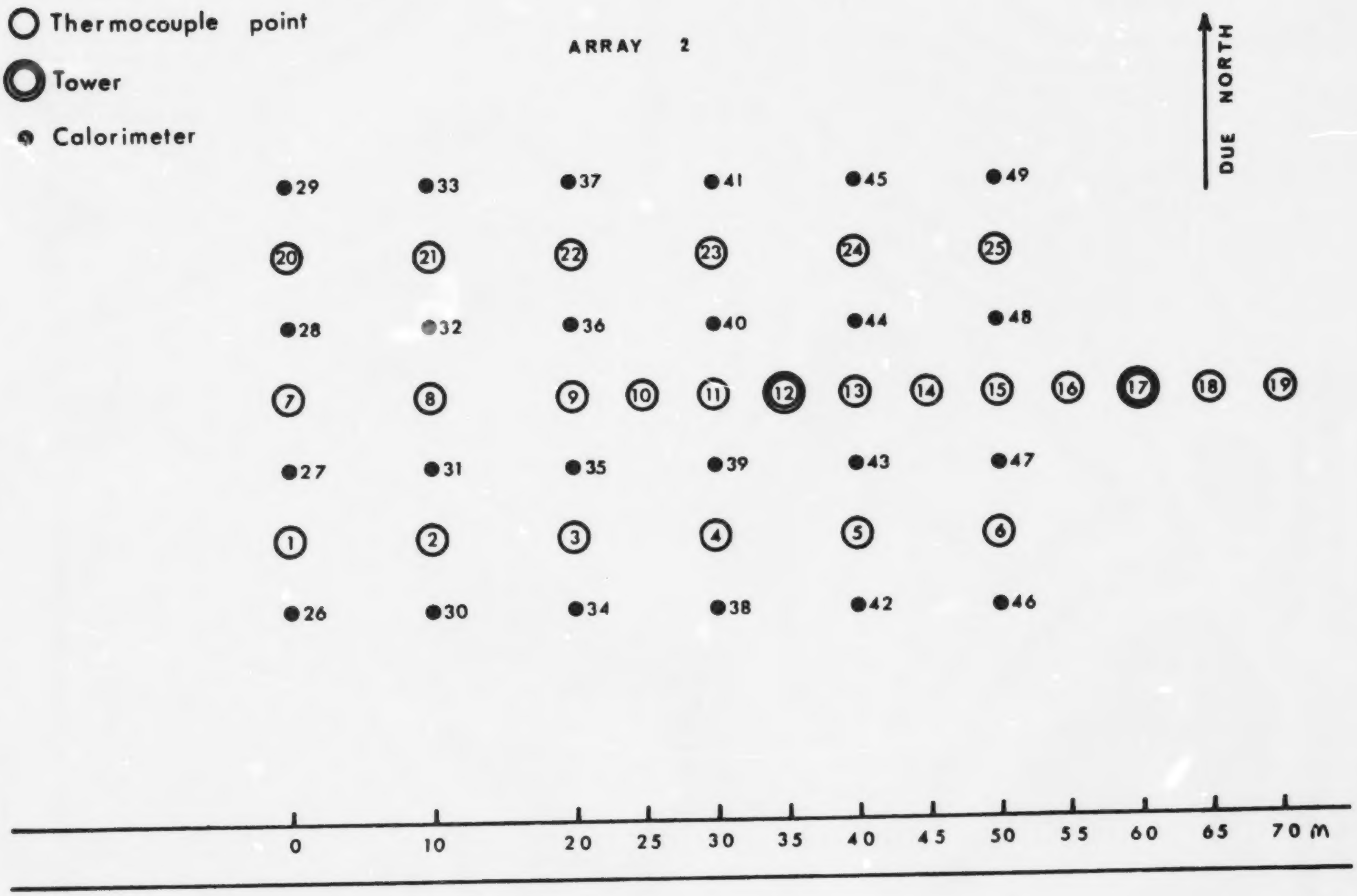

Thermocouple point
Tower
Calorimeter
ARRAY 2
DUE NORTH
29
33
37
41
45
49
20
21
22
23
24
25
28
32
36
40
44
48
7
8
9
10
11
12
13
14
15
16
17
18
19
27
31
35
39
43
47
1
2
3
4
5
6
26
30
34
38
42
46
0
10
20
25
30
35
40
45
50
55
60
65
70 M

FIGURE 13. Plan for 1971 CFS fire research micro-plots at instrumentation setting "Array 2".

micro-plots within a given treatment plot. Individual plans of each plot (e.g., Fig. 3) are invaluable for plot relocation, verification and study; these should show stems, slash, stumps and similar features. In discussing the relocating of permanent sample plots, Johnson noted that most note-takers do not supply enough fine detail; copious notes with lots of detail are desirable.[5]

Photographic records should use an object for scale (e.g., Mr. Wright used his axe). Documentation should indicate focal length of lens used, and location and direction from which photos are taken. Camera databacks are now available that enable imprinting of data and micro-plot information into the film; their use can greatly facilitate proper documentation. Negatives and slides must be stored in materials that will not alter their chemistry over time.

4.2 Permanent Markings in the Field

Permanent markings in the field are indispensable to proper relocation of past research sites (most compasses we use have limited accuracy and precision that can compromise relocation from field notes). Also, there is nothing more reassuring than finding micro-plot evidence at the end of a long survey. Permanent markings must be subject to a number of considerations involving the material used for marking and the actual marking technique (Table 5). When selecting a marking technique one must consider using land marks and decreasing the opportunity for vandalism. In putting a rock on a stump, Mr. Wright took advantage of prominent land marks, and the highly visible rock was not very prone to vandalism (most rocks do not make good fenceposts, targets, or mantle-piece ornaments). This represents one approach to plot marking in which the highly visible "monument" (e.g., Mr. Wright's rock on a stump) was tied into the actual plot marker, in this case a railroad spike. For the past 20 years, Swiss foresters have been using "invisible permanent samples" (buried markers) for their permanent forest inventory system that employs prominent landmarks as starting points (Schmid-Haas 1983, 1985). Their rationale stems from a desire to prevent the local forester from knowing the location of growth and yield plots, which might bias stand management and result in incorrect characterization of the surrounding forest. Monuments and micro-plot markers should be permanently numbered with engraving or numbering stamps to facilitate resampling. Inclusion of map and sampling information (e.g., well-hidden plaques showing plot locations, stem maps, sampling crews and dates) might be considered as field "time capsules" (Dr. K. Iles, Biometrician, pers. comm., MacMillan Bloedel Ltd., Nanaimo, B.C.).

TABLE 5. Considerations for permanent plot markers

Use landmarks and/or monuments (e.g., rocks on stumps can last 42 years)

Materials

Utility

- ease of relocation (e.g., visibility, metal detection, monument)
- ease of placement
- ease of transport to field location

Long-term hardiness

- resistance to vandalism (sturdiness, attractiveness)
- decay/oxidation resistance
- nutrient or toxin release confounding results (e.g., copper)

Overall costs

Field Markings

Numbering
Location data
Site data and sampling crews recorded in field

Safety

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[5] Johnson, R. 1985. Lessons learned in relocating abandoned "permanent" plots. Unpubl. Circ., Washington Off. Timb. Manage., 4 p.

Materials used for monuments and micro-plot marking must be evaluated for facility, cost, and hardiness in a long-term perspective (Table 5). Mr. Wright's railroad spikes have lasted well but may have released some iron into the environment; aluminum pipe is used for the 20-year-old Swiss plots (Schmid-Haas 1983) and 15-year-old aluminum angle still appears in new condition at the CFS Mission Tree Farm plots. Johnson noted that blazed "witness" trees at the edge of permanent plots and 2-inch (5 cm) diameter, thick A1 tree tags with large A1 nails have proven successful for at least 15 years.[6] Although A1 is a potentially toxic element and of interest in our studies, it appears quite resistant to release by weathering. (In some locations, A1 angles have been stolen and different or back-up marking/materials must be considered). Safety must also be considered; Trowbridge *et al.* (1986) recommended bending the ends of metal rods lest a person or animal be impaled.

An example of current research demonstrating a number of good documentation procedures is the slashburning research by MacMillan Bloedel Limited in the Sproat Lake Division on Vancouver Island (Beese 1984, 1986). Large numbered steel fenceposts are used for corner posts that have been located on large-scale aerial photographs, thus producing detailed setting maps with plot features (Fig. 14). (I have been assured that the stumps on the maps will be marked with rocks.)

5 CONCLUSIONS AND RECOMMENDATIONS

We must not let past research experience such as Mr. Wright's go unheeded. We need knowledge of the long-term effects of forest management practices on forest productivity. By resampling past research sites, such as Mr. Wright's, we may fill an important information gap by providing (1) some quantititive data on these long-term effects now, (2) some experience from which to improve on our current research efforts, and (3) an increased range of site conditions with data on treatment effects. Although past research plots invariably possess data sets that have a number of limitations, they none-the-less provide a unique opportunity to return to and study an area for which there is a record of past forest management. Through the study of these past sites we can also gain experience in answering many of the perpetual questions we face in designing research.

The following conclusions and recommendations are offered:

1) Past research sites can be very useful for the study of long-term site degradation.
    1a) In addition to their originally intended uses, past research sites can also offer a wealth of other information (e.g., treatment effects on competing vegetation).
2) Past research attests to the usefulness of using micro-plots which enable more meaningful evaluation of long-term site degradation by providing large paired-data sets for the study of relationships between site preparation characteristics (e.g., fire behavior and fire impact) and their effects on tree growth and nutrient levels.
    2a) The large paired-data sets from the micro-plot approach complement a number of other studies (e.g., forest ecology).
    2b) All available evidence suggests that the micro-plot approach is presently the best approach to the long-term study of prescribed fire effects.
    2c) Micro-plot sampling may be designed to represent large plots with more units of record, providing the micro-plot advantage without too much extra investment.
    2d) Limitations of the micro-plot approach need to be considered more closely for each application.
    2e) Micro-plot relocation can be facilitated by systematic sampling designs (e.g., grid systems with a random start) and plans for each microplot (e.g., Fig. 3).
    2f) Long-term study of treatment effects using micro-plots can be refined by (i) the data analysis of the initial treatment impact (e.g., if you end up with 10 plots of "low" impact and 4 of "high" impact, you might just select 4 of each for long-term study), and (ii) providing for the destructive effects of sampling (e.g., Curran [in press] planted four trees per micro-plot).

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[6] Ibid.

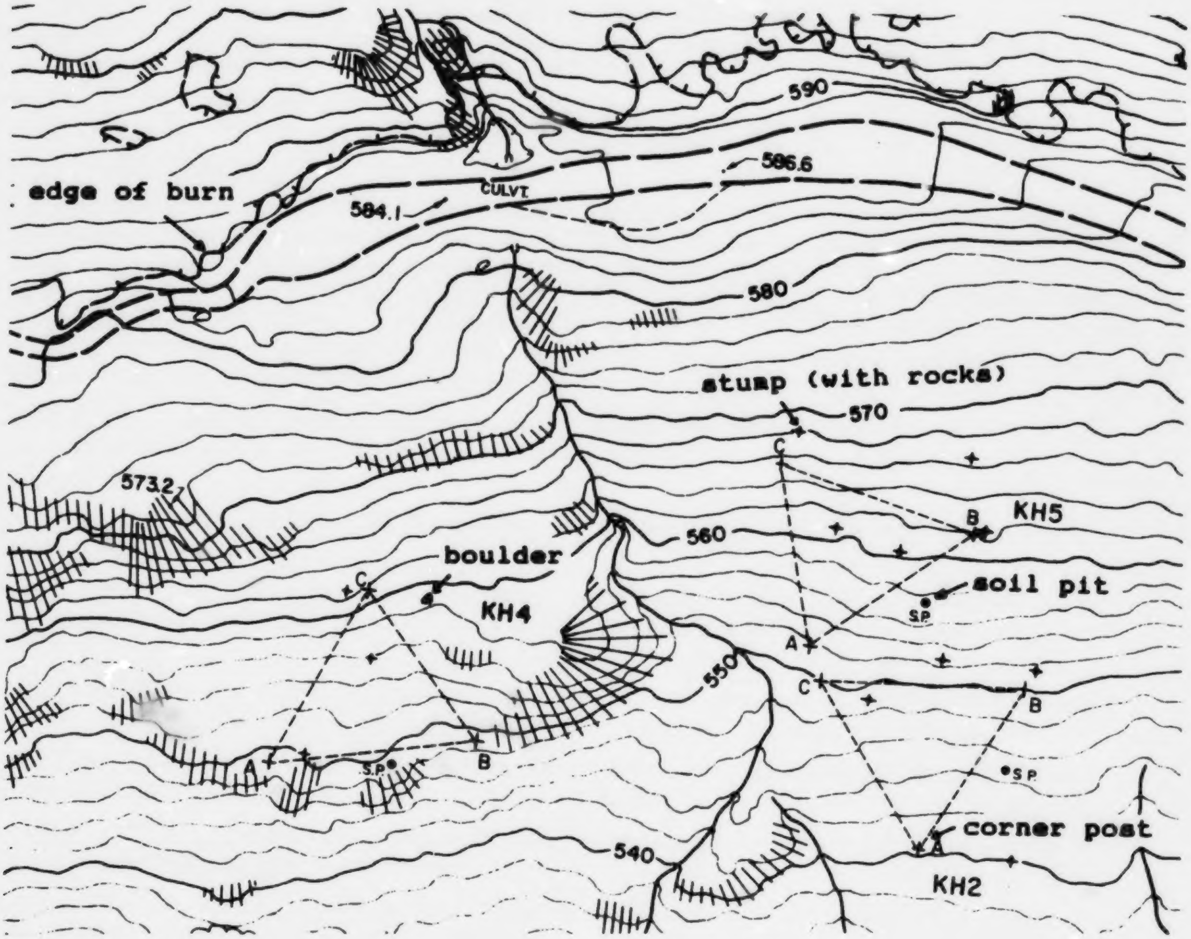
edge of burn
590
586.6
CULVT
584.1
580
stump (with rocks)
570
573.2
C
B
KH5
560
boulder
C
KH4
soil pit
S.P.
A
550
C
B
A
B
S.P.
S.P.
corner post
540
A
KH2

FIGURE 14. Example of plot detail from setting map for MacMillan Bloedel fire research plots near Sproat Lake on Vancouver Island (scale 1:1000, contour interval 2.0 m).

2g) Micro-plots may be altered to allow for testing of various levels of site impact. For example, Curran (in press) loaded more fuel on some micro-plots to attain higher burning intensities on those plots. If not accounted for, this would complicate the characterization and interpretation of natural impact conditions, but provide more data points at the extremes as is desirable for regression analysis (Demaerschalk and Kozak 1974; Hawkes [in press]).

3) Documentation of current research must be improved to enable possible resampling in the future, especially through the use of permanent field markings.

3a) Past research can suggest which documentation techniques have stood the test of time.

3b) Documentation must preserve the integrity of the micro-plot approach.

3c) Rocks on stumps work very well (for the first 43 years).

6 ACKNOWLEDGEMENTS

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SESSION 6 RESEARCH NEEDS

DEGRADATION OF FORESTED LAND: RESEARCH NEEDS

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1 INTRODUCTION

Over the past two days we have been privileged to hear many interesting, informative and thought-provoking presentations relating to forest soil degradation in British Columbia, and in general. From these presentations I am sure you are all capable of defining for yourselves what the major problem areas are, where the major information gaps appear to be and therefore, in a general sense at least, what direction future research ought to take. My purpose in standing before you now is to present you with my perspective on that issue.

The following list of "research needs" is not intended to be exhaustive. There will no doubt be potential areas of research that I do not touch on at all, and others that some will think I have inadequately addressed. For the purposes of this presentation I am a B.C. Forest Service employee and, for that reason, certain research needs have a higher priority for me.

It is no doubt common knowledge that the B.C. Forest Service administers the forest resources of this province by virtue of its mandate as described in the Ministry of Forests Act and the Forest Act. From the Ministry of Forests Act we are given the following (paraphrasing somewhat):

The purposes and functions of the Ministry of Forests and Lands are (amongst other things):

(a) to encourage maximum productivity from forest and range land;

(b) to manage, protect and conserve the forest and range resources having regard to immediate and long-term economic and social benefits; and

(c) to plan and use forest resources in a coordinated and integrated fashion.

Thus, the Ministry has a strong mandate to maintain and enhance forest productivity, and to understand the socio-economic consequences of its management activities. These requirements, in turn, define in a general way what our knowledge requirements are:

(1) We need to know how best to assess, or quantify, site productivity and changes in site productivity, so that we can set a realistic rate of harvest, define areas producing below potential, evaluate the effects on productivity of our management and rehabilitation efforts, and evaluate the short- and long-term economic consequences of our actions.

(2) We need to know how we can prevent or minimize site productivity losses so that we can achieve maximum productivity.

(3) We need to know how best to improve productivity, so that we can practice effective rehabilitation and help realize maximum productivity. The following represents what I think are some of the more pressing research needs.

2 ASSESSING/QUANTIFYING PRODUCTIVITY AND CHANGES IN PRODUCTIVITY

Above all else, we need to be able to assess site productivity reliably, as well as changes in site productivity resulting from forest management impacts. The capability of making such improved assessments will facilitate two things:

(1) It will allow the Chief Forester to set realistic AAC's based on a more reliable estimate of sustainable yield, and modify those AAC's in consideration of site productivity changes resulting from forest management impacts.

(2) It will facilitate the development of realistic economic analyses, and thereby provide insight into the economic tradeoffs available to accomplish forest management objectives. For example, if productivity losses owing to ground skidding on a particular management unit can be reliably estimated, then the extra cost associated with cable harvesting that same unit can be weighed against the attendant reduced site disturbance. In addition, the cost of soil productivity rehabilitation could be meaningfully compared in the same analysis.

The ability to make the necessarily reliable estimates of site productivity and site productivity changes appears to me to be contingent upon the development of strong quantifiable relationships between those things and certain site factors. While a considerable amount of growth reduction information related to soil compaction exists for the Pacific Northwest United States (Froehlich and McNabb 1984), there is not much of the same for British Columbia. In any event, this information does not provide us with long-term information on productivity reductions. So, I believe we must carry out a long-term research effort directed at ascertaining the effects of various kinds and degrees of soil disturbance on site productivity. The intent of such an effort, at least initially, should be to provide baseline estimates of productivity and productivity changes by tree species, climatic regime, and soil "type" as defined by selected soil parameters such as bulk density and texture.

In a little more general sense, we also need to develop a sound understanding of the effects of various forest management activities on site productivity. In terms of forest management, I would suggest that we need to continue to evaluate the biological effectiveness of such practices as slash burning, scarification, and herbicide use. In some cases, on some sites, each may be a cost-effective option which does not adversely affect long-term site productivity. However, I also believe that under some circumstances each may have a potentially adverse impact overall. I think it is important to quantify the productivity gains or losses we are likely to realize with the application of such practices, so that we can define which sites are best suited to each alternative.

An additional related problem for us here in British Columbia is that we have not as yet established a relatively simple, quick and reliable method for estimating the extent and nature of soil disturbance over an area. While a number of proposals exist for doing so (Howes *et al.* 1983; Smith 1985.[1] Thompson and Still 1984[2]), we have not, to the best of my knowledge, adequately field tested or refined any of them. I would therefore suggest that the development and testing of a cost-effective system for reliably measuring or estimating the nature and extent of soil disturbance is a high priority in this province. It may be that a suitably accurate and simple system already exists and has been tested elsewhere, so that adequate testing in British Columbia maybe the only real need.

3 PREVENTING/MINIMIZING PRODUCTIVITY LOSSES

Minimizing the extent of detrimental soil disturbance is perhaps the most logical way to minimize productivity losses and, hence, maintain or maximize productivity. I believe there are a number of facets to this issue.

First of all, I believe we need a good site assessment system which takes account of important factors and allows for a reliable assessment or prediction of site sensitivity. It is imperative that site sensitivity be evaluated prior to the implementation of any particular management activity or management regime. The B.C. Forest Service is currently in the process of implementing just such a preharvest site assessment system; so, the development of the same is not a critical research need, per se. However, I would stress that its successful implementation will play an important part in minimizing soil productivity losses in British Columbia. In conjunction with the implementation of this system, there must also be an ongoing effort to validate and improve it in order to ensure its usefulness as a site diagnosis tool.

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[1] Smith, R.B. 1985. Very deep soil disturbance - interior B.C. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Unpublished report. 4 p.

[2] Thompson, S. and G. Still. 1984. Working plan for evaluating a method for determining soil disturbance following logging in the Nelson Forest Region. B.C. Min. For., Nelson, B.C. Unpublished report. 20 p.

It is also important that we develop and test systems for the evaluation of site sensitivity itself, based on an inventory of selected site features such as would be collected in the preharvesting phase. Sites may be sensitive to a variety of forest management impacts. The evaluation of the sensitivity of a given site to each may require slightly or radically different information inputs. In addition, we do not always know what site features might be important in determining sensitivity to various impacts. Site assessment requires an understanding of what factors to include, and how to integrate that inventory information into a meaningful index of sensitivity. For example, factors determining a site's sensitivity to detrimental compaction are different from those that affect its sensitivity to mass wasting or erosion, or its susceptibility to nutrient losses through slashburning (Food and Agricultural Organization of the United Nations 1973; Daykin *et al.* 1981; Vold 1981.[3] Still and Utzig 1982). I believe a considerable research effort could be usefully directed at developing reliable methods for evaluating site sensitivity to various forest management activities.

Another facet of minimizing productivity losses relates to the prescription of appropriate harvesting systems (i.e., those best suited to the terrain and climatic conditions) and the need for careful inventory, planning and layout of the forest harvesting operation. It is clear to me that the prelocation and designation of skid trails, for example, can help minimize detrimental soil disturbance (Adams and Froehlich 1981; Froehlich *et al.* 1981; Froehlich and McNabb 1984; Olsen and Seifert 1984). I believe that the logistical and economic viability of such alternatives as skid trail prelocation and designation warrant extensive testing in British Columbia.

Further to this, I believe that, with an increasing trend toward the managed stand regime, there may be a need to look at the long-term effects of intensive forest management. Under this category, some of the higher priority issues include the effects of increasing mechanization, of thinning and fertilization, and of periodic, large-scale biomass removal.

Similarly, we know that certain kinds of harvesting equipment tend to have a high adverse impact on site productivity on some sites (Wellburn 1974; Smith and Wass 1980; Schwab and Watt 1981). Ground skidding on steep slopes is an example. This follows logically as a result of the greater excavation required to build skid roads as slopes get steeper. So, I see a need to develop and test new, low-impact harvesting equipment and systems.

The effects of roads and roadbuilding on productivity must be better understood. We know that roads themselves are effectively lost from production, but there is evidence that timber adjacent to road rights-of-way may tend to grow better, possibly because of less competition and better overall light conditions (Megahan 1985). Is this universally true? Does the improved growth (when it occurs) entirely offset the loss of productive land used for roads? What about the interception of subsurface flow in terms of its effect on the productivity of sites downslope?

I believe these are all issues that warrant research.

4 REHABILITATION OF SITE PRODUCTIVITY

The ultimate objective for soil rehabilitation work is to select the most cost-effective means of achieving a desired soil condition, or of rehabilitating site productivity. The first step in accomplishing cost-effectiveness involves selecting appropriate sites for rehabilitation. In order to do this, it is important to know which sites have been sufficiently affected so as to warrant a rehabilitation effort. I have already, to some extent, discussed this issue in terms of knowing how to quantify productivity, and in terms of knowing what kinds of soil disturbance and/or forest management practices result in varying levels of reduced productivity.

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[3] Vold, T. 1981. Soil interpretations for forestry. B.C. Min. Environ., Victoria, B.C. Unpublished discussion paper. 90 p.

It is already sufficiently clear that certain kinds of forest soil disturbance represent a significant loss of productivity. Compacted landing surfaces, especially on steep slopes, can safely be assumed to have lost the major part of their productive potential. It is not clear that cost-effective rehabilitation of productivity could take place on these areas. On the other hand, some skidroad surfaces, or parts thereof, are not likely to be severely disturbed, so that recovery of significant productivity from such areas might be expected from a relatively inexpensive rehabilitation effort (W.W. Carr, Terrasol, pers. comm.). I think we need to know where our most cost effective rehabilitation opportunities lie, and what rehabilitation systems or techniques work best under different circumstances. It is probably not possible to recreate strictly original soil conditions, and it is probably not necessary to do so in order to achieve original levels of soil productivity. With this in mind, I believe there is a need to evaluate the effectiveness of new rehabilitation techniques and/or systems by measuring subsequent tree growth and productivity.

An understanding of how forest management impacts have changed the chemical, physical, and biological characteristics of the soil from the original condition, and how those changes might have affected tree growth and productivity would be useful in our efforts to develop and test soil rehabilitation techniques and materials. I have already discussed the importance of understanding relationships between productivity and other site factors, so will not reiterate at this point.

In terms of developing new rehabilitation techniques, there appears to be a need to test various mechanical methods for rehabilitating soil productivity, alone and in combination with soil amendments such as using fertilizers and organic matter or seeding with grasses and legumes. A complementary line of research involves the development and testing of specialized soil rehabilitation equipment to establish the most effective means of recovering favourable soil physical properties. It is probable that different soil tillage equipment and green fallow mixes may rehabilitate soil productivity to varying degrees on different sites (Lull 1959; Greacen and Sands 1980; Froehlich 1984). It is therefore apparent that some research should be directed at determining which systems work most effectively on which sites.

Soil rehabilitation must also be viewed from the perspective of mitigating physical soil loss resulting from erosion and mass wasting. As I have already pointed out, predicting site sensitivity to such processes and prescribing appropriate systems is the first major step involved in minimizing the impact. However, given that erosion and mass wasting will occur from time to time, we must have effective and cost-effective means of minimizing physical soil loss, both because of the need to minimize productivity losses, and because of the potential adverse off-site effects, such as degraded water quality and fish habitat (not to mention aesthetics).

There is a considerable body of knowledge available pertaining to erosion control and, to an extent, rehabilitation of unstable areas. Cost-effectiveness, particularly in respect of rehabilitating unstable areas, is difficult to ascertain and perhaps requires some research effort. In addition to the need for continued development of new techniques for erosion control, mass wasting "control" and hazard prediction, I think that we, in British Columbia, need to refine the available techniques through operational trials over the range of climates, soils and topography in this province. Two higher priority issues along these lines include the testing of geotextiles, and more extensive experimentation with native shrubs for erosion control.

5 IN CONCLUSION

I have a few remarks to make in conclusion.

I acknowledge that I have only barely touched on the issue of off-site effects of forest soil degradation. While this issue is of no small consequence, the off-site effects of forest management practices have received considerable attention in the past. I feel, therefore, that research needs and priorities in respect thereof may already be fairly well defined.

I have also neglected to mention specifically the range resource in my presentation, despite the Forest Service mandate to manage it in addition to the forest resource. This is primarily because the major thrust of this workshop was forest soils per se. Nevertheless, I believe that some of the research needed to address forest soil degradation issues can be directed at range soil degradation as well. This is especially true of assessing productivity and productivity changes and, to some extent, is also true of the rehabilitation of range soils.

In the course of my presentation, I have glibly pointed to what could amount to millions of dollars of potential research. I am labouring under no delusions regarding the likelihood of acquiring that kind of funding. I do believe that what I have presented could be pieced together into a comprehensive, multi-faceted, long-term research initiative. At this point, however, it is much more important to priorize those research needs in consideration of available funding. For example, we should concentrate on research or development work that is likely to provide us with significant gains in the short run. Being able to predict site sensitivities reliably and prescribe appropriate management systems seems to me to be of a higher priority than some of the other issues I have identified. In discussion with many of my colleagues over the last few months, the need for prevention of soil degradation, in the first place, was the point which was most often "driven home."

I also think that one of the most pressing needs in British Columbia is the establishment of soil disturbance/site productivity reduction relationships. In the absence of that information, we are compelled to borrow from the U.S. research results. While I have no doubt that we are likely to find trends similar to those found in the U.S., it is important that we quantify those trends for our own conditions so that our AAC can realistically reflect the land's capability to produce timber. In a related vein, it is important that we develop or adopt a system for measuring or estimating detrimental soil disturbance on an operational basis. This must be done soon, so that we can begin to monitor and quantify forest soil degradation in British Columbia effectively, and modify our management practices accordingly.

Finally, I would point out that, while there are obviously many research needs related to forest soil degradation in British Columbia, simply providing answers or research information will only go part of the way towards solving our problems. There is a very real need for extension work with operational foresters, and, in general, a real need for professional and public acuity about forest soil degradation. This means that there must be an administrative and financial commitment both to solving some of these problems and to ensuring that important information is adequately disseminated and appropriately used. Without that kind of understanding and commitment, forest soil degradation in British Columbia is destined to become an increasingly large reality.

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POSTER PRESENTATIONS

HARVESTING GUIDELINES FOR THE VERNON FOREST DISTRICT: CONTOUR STRIP LOGGING, SKIDROADS AND LANDINGS[1]

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1 INTRODUCTION

Excessive soil disturbance resulting from construction of skidroads and landings may result in surface erosion, soil compaction, slope failure, burying or removal of soil layers, exposure of subsurface soil layers and/or impairment of the normal movement of nutrients and water. This could mean loss of site productivity and/or adverse impacts on other resources, such as water quality. If measures are not taken to minimize or prevent excessive soil disturbance during the harvesting/post treatment phase, there are rarely any opportunities to correct the problem in the future. For practical purposes, the productive soil land base is not renewable.

The B.C. Ministry of Forests and Lands has begun preparation of a Timber Management policy and procedures on site degradation. The policy may require a lengthy period to develop and may require significant changes in the types of equipment and procedures used in harvesting operations. The objective of the following guidelines is to provide some direction in the interim that will minimize site degradation, yet be feasible for the equipment currently in use in the Okanagan Timber Supply Area (TSA).

2 STANDARDS AND PROCEDURES

2.1 For Contour Strip Logging:

2.1.1 Size, shape and pattern (Figure 1)

a. Long, narrow and oriented along the contours.

b. Average of 250-350 m wide with a reserve separating (across the contour) each strip. The reserve block should be as wide or wider.

c. Length of strips is unlimited, but they should be broken with sufficient wildlife corridors to permit unimpeded movement of the animals.

2.1.2 Sequence and timing of harvest

a. When a contour strip is long enough that it will not be completely logged within one season, or when multiple treatment units have been identified, then the contour strip should be divided into individual blocks that coincide with the treatment units and/or sequence of harvesting. A treatment unit is defined as a harvesting unit that prescribes only one silviculture system and one harvesting system.

b. Where warranted by slash hazard, blocks should be kept to manageable sizes (usually less than 30 ha) and staggered so that logging of intervening blocks does not proceed until the burning has been completed on adjacent blocks.

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[1] Guidelines derived for November 1985.

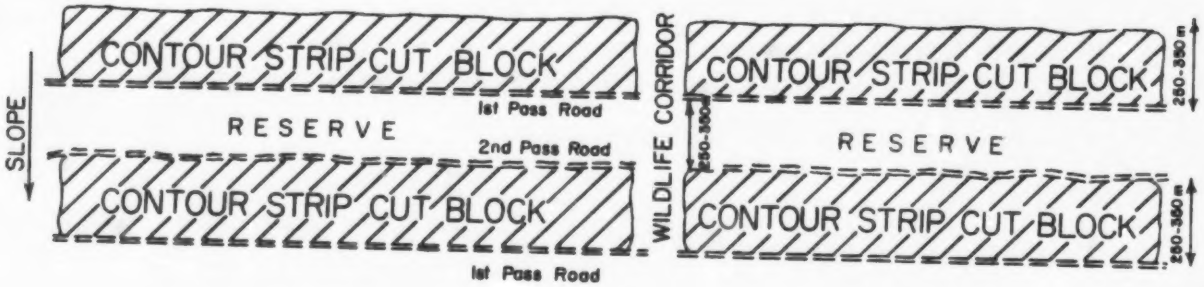
SLOPE
CONTOUR STRIP CUT BLOCK
1st Pass Road
RESERVE
2nd Pass Road
CONTOUR STRIP CUT BLOCK
1st Pass Road
WILDLIFE CORRIDOR
250-350 m
CONTOUR STRIP CUT BLOCK
250-350 m
RESERVE
CONTOUR STRIP CUT BLOCK
250-350 m

FIGURE 1. Contour strip layout.

c. Wildlife corridors may be harvested when adjacent "green-up" has been attained. "Green-up" is defined as satisfactory restocking with established tree species that are acceptable to the site and have reached at least 3 m height or 1 m above the average snowpack, whichever is greater. Stocking shall meet the standards specified by the Ministry of Forests and Lands.

d. Portions of the reserve blocks may be logged during second pass once green-up has been attained on the original contour strips. Travel corridors and well-distributed thermal-cover units should be maintained for wildlife. Thermal-cover units may double as travel corridors.

e. Third pass logging of thermal units and travel corridors may proceed when the original blocks satisfy the wildlife requirements (or the thermal units and corridors no longer satisfy these requirements).

2.1.3 Application

a. Generally, contour strip logging should be applied on sideslopes where the parallel road system will result in less total road construction and lower overall road grades.

b. As part of an engineered series of strips on a sidehill; not a single strip designed to maximize block size.

2.2 For Skidroad Location, Construction and Rehabilitation

2.2.1 Maximum allowable soil disturbance from skidroads, spur roads and landings (disturbance is defined as gouges or deposits greater than 25 cm deep)

a. Low and moderate sensitivity (Table 1): 15%

b. High and very high sensitivity: 10%
- exclusive of main and branch roads that access other blocks

2.2.2 Maximum depth of cut on skidroads

a. 1 m

b. Larger cuts remove more topsoil, intercept more ground water and increase the risks of slope failure and erosion

2.2.3 Skidroad spacing

a. 30 m slope distance is recommended as a minimum. This will have to be increased as slope increases, to stay within the maximum allowable disturbance levels.

b. Narrow skidroad spacing increases the risk of slope failure and produces more compaction and detrimental displacement.

2.2.4 Skidroad location

a. Preferably on benches.

b. Inclined skidroads should be waterbarred to divert surface runoff (Figure 2).

c. On skidroads with steep grades (i.e., > 20%), excavation should be kept to a minimum so that surface runoff is not channelled. Erosion hazard increases in grade.

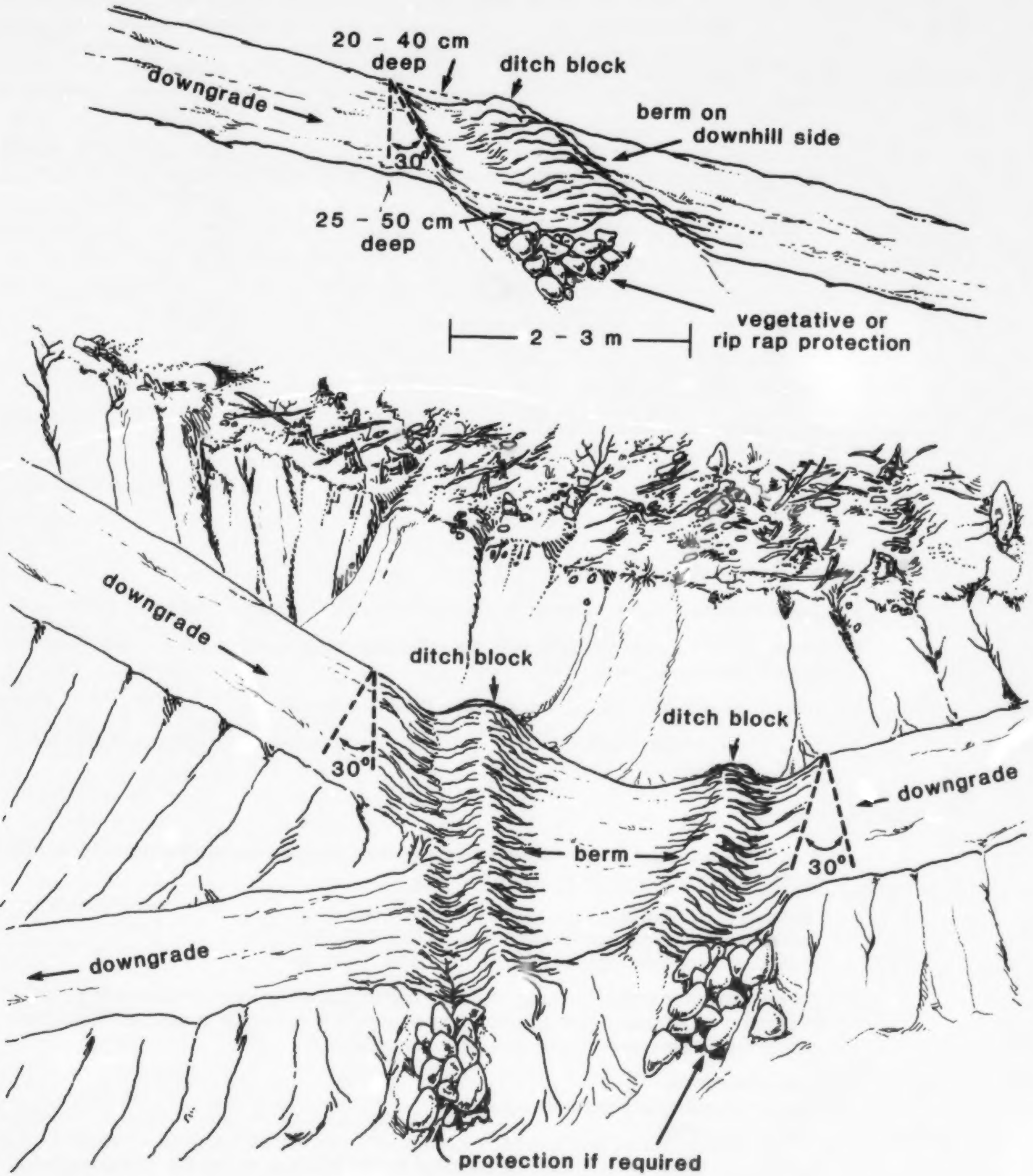
20 - 40 cm
deep
ditch block
downgrade
berm on
downhill side
30°
25 - 50 cm
deep
vegetative or
rip rap protection
2 - 3 m
downgrade
ditch block
ditch block
30°
downgrade
berm
30°
downgrade
protection if required

FIGURE 2. Water bars.

TABLE 1. Sensitivity to site degradation from timber harvesting

Slope (%)		Soil Depth (cm)[a]		Sensitivity
60 or evidence of existing mantle failure on any slope				- very high
46-60	-	50		- very high
	-	50	clays, sands	- very high
			loams	- high
30-45	-	50	clays, sands	- very high
			loams	- high
		50	seepage	- very high
			no seepage clays, sands	- high
			loams	- moderate
30			seepage	- moderate
			no seepage - clays, silty-wet	- moderate
			- dry	- low
			- loams (not silty), sands	- low

[a] Depth: the depth to bedrock, to a restricting or compact layer, or to coarses and and/or more than 70% coarse fragments.
Seepage: fluctuating or permanent water within the subsoil (subhygric to hygric moisture regimes).
Dry: seasonally moist to wet soils in the upper 50 cm.
Texture: clays (C1, SCL, SiCL, SiC, SC, C), loams (L, SL, SiL, Si); sands (S, LS); silty (SiCL, SiC, SiL, Si).

(Adapted from: Mitchell W.R. 1984. Draft proposal of "Guidelines for timber harvesting practices in the Kamloops Forest Region." B.C. Min. For., Kamloops, B.C.)

2.2.5 Stream crossings

a. Should be constructed to minimize disturbance of stream channel or disruption of stream flow.

b. Winter crossing: snow bridge is adequate providing that gouging of stream bank does not occur during construction.

c. Intermittent seepage flow: parallel logs with dirt fill is adequate.

d. Steady flow or heavy intermittent flow: metal culvert or wooden culvert with log sill abutments and log stringers.

2.2.6 Rehabilitation

a. Prior to the next breakup, skidroads should be rehabilitated to maintain the natural drainage pattern and minimize surface runoff, including:

- removal of all crossings over natural drainage channels
- grass seeding where erosion hazard exists (see Table 2)
- construction of cross-ditches (water bars) (Table 3, Fig. 2)

b. Special measures should be taken on winter-logged cuts which block tributaries to sensitive fish habitat or domestic water supplies, and where it is not possible to establish water bars prior to the next breakup. Some alternatives are (Table 4):

- snow skid trails
- random skidding with flex-track equipment
- cable harvesting

Additionally, these areas should be patrolled by the licensee during the spring freshet to ensure that natural drainage patterns are maintained.

TABLE 2. Surface erosion hazard criteria
(Circle appropriate rating value and total below for hazard rating)

Environmental Factors	Degree of Contribution of the Factors			
	Low	Moderate	High	Extreme
CLIMATE				
Mean Annual Precipitation (mm)	2 <400	4 400-699	6 700-1200	8 >1200
TOPOGRAPHY				
Slope Gradient (%)	3 0-15	6 16-30	9 31-60	12 >60
Depth to Restricting Layer (cm)	2 >90	4 61-90	6 30-60	8 <30
SURFACE SOIL DETACHABILITY				
1) Moist Consistence or	1 very firm	2 Firm	3 Friable	4 Loose
2) Texture	1 SC, C HC, SiC	2 SiCL,CL SCL	3 SL,L SiL	4 LS, S Si
SUBSOIL PERMEABILITY				
1) Texture or	1 S, LS, SL	2 L,SiL,Si	3 CL,SCL, SiCL	4 C, HC SC, SiC
2) (%) Coarse Fragments	1 75	2 50-75	3 25-49	4 25

Hazard Rating Values

Low	20
Moderate	20-24
High	25-29
Extreme	29

(From: Mitchell W.R. 1984. Draft Proposal of "Guidelines for timber harvesting practices in the Kamloops Forest Region." B.C. Min. For., Kamloops, B.C.)

TABLE 3. Recommended spacing for cross-ditch construction[a]

Erosion Hazard (From Table 2)	Gradient (%)	Maximum Spacing (m)	Grass Seeding
Low	<20	150	No
	≥20	90	Yes
Moderate	<20	90	Yes if > 5%
	≥20	30	Yes
High	<20	30	Yes if > 5%
	≥20	15	Yes
Extreme		15	Yes

[a] N.B. It is important to provide a cross drain immediately above steep pitches (> 20%) and below bank seepage spots.

TABLE 4. Harvesting recommendations

Slope %	Sensitivity (From Table 1)	Harvesting System	Equipment
30	low	random skidding[a]	conventional
	moderate	random skidding	low ground pressure or conventional on frozen ground or snow
30-45	moderate	conventional	conventional
	high to very high	modified[b]	conventional or alternative[c]
46-60	high	modified	conventional or alternative
	very high	modified	alternative preferable cable
60 or evidence of existing mantle failure	very high	location of roads is critical	cable, preferably skyline, or helicopter

[a] No blade-constructed skidroads except for return trails. Exceptions: deep snow conditions or decadent timber types with large stumps.

[b] A modified harvesting system on steep slopes eliminates excessive skidroad excavation by such methods as random skidding or construction of skid trails on the snowpack.

[c] Alternative equipment does not require skidroads, e.g., cable, low ground pressure or helicopter.

2.3 Landing Location, Construction and Rehabilitation

2.3.1 Location

a. Maximum area of land within any one cutblock which may be disturbed for landings:

- 3.5% (low to moderate sensitivity)
- 2.5% (high to very high sensitivity)
- exception - blocks smaller than 14 ha

b. Landings should be kept as small as practical. On steeper slopes, larger landings increase the risk of surface erosion and slope failure.

c. On poor and low sites and/or where landings are less than 0.1 ha in size and less than 1% of the block area, ripping and the respreading of topsoil on landings will not be required (2.3.2 a, 2.3.3 a,b).

d. All landings and landing debris should be kept a minimum of 40 m from all:

- swamps and water courses;
- designated immature timber which is reserved from cutting (with the exception of selective logging); and
- cutblock edges (except where a road forms the boundary, in which case the buffer may be reduced to 20 m).

e. Where feasible, all landings and landing debris should be kept a minimum of 100 m from all:

- fish-bearing streams; and
- permanently flowing streams having domestic water licences.

f. These guidelines should not preclude placing a landing in the best possible location for minimizing any negative impacts on the environment. A small bench closer to a creek is often preferable to heavy excavation on a sidehill further away. When landings are located as close or closer than the above specified distances, it is important that no slash or debris is pushed closer. This will require extra supervision.

g. Landings should be constructed with adequate drainage to prevent ponding. They should also be located so as to prevent runoff from flowing onto the landing. Diversion ditches may be used to direct surface runoff away from the landing.

2.3.2 Construction

a. The upper layers of soil should be piled on the landing and made accessible for respreading. Most of the nutrient capital of a soil is concentrated in the upper organic layers plus the A and B horizon. Most of these layers are included in the upper 25 cm of soil. All of the upper organic layers (duff) and as much of the underlying 25 cm of soil as is practical should be saved.

- **exceptions:**
  - rocky conditions which preclude soil removal
  - steeper slopes (>15) where operational problems or the larger landing size needed to store the soil do not justify the benefits
  - poor and low sites
  - if landings <0.1 ha and <1% of the block area

b. A concentrated cull pile for all combustible debris should be designated within the confines of the landing and should be made accessible for respreading after burning. To minimize landing size on steep slopes, it may be preferable to locate the cull pile on the fill slope, thus precluding respreading. The combustible debris should be piled at least 5 m from adjacent slash and be surrounded by a mineral soil fireguard, except on sites to be broadcast burned.

c. Stumps may be disposed of by one of the following methods:

- pile stumps with the topsoil pile for respreading after burning. The stumps will replenish some organic matter as they decompose, provide dead shade for seedlings and discourage vehicle traffic on the landing.
- move stumps with as little soil as possible and scatter them around the periphery of the landing.
- separate stumps from the soil and pile them with the other combustible debris for burning. It is important not to mix soil in with the debris pile, as this often leads to hangover fires.
- completely bury stumps under a minimum of 1 m of soil. It is important that stumps are not partially exposed as they could catch fire during debris disposal and lead to an underground fire.

2.3.3 Rehabilitation:

a. Where operations have caused compaction of the landing surface and it will not be used again before the next rotation, the landing should be ripped to a depth sufficient to break up the compacted layer. The compaction usually extends from the surface to a depth ranging from 40 to 80 cm, depending on soil type and machine activity. Compaction adversely affects tree root growth, infiltration, and the moisture holding capacity of the soil. Ripping should follow as soon as possible after logging or site preparation. The soil should be dry enough (< 25% moisture content) to achieve adequate fragmentation.

b. Topsoil and the remains of the debris pile should be spread over the landing if they will not be used again before the next rotation. Spreading should follow as soon as possible after logging or site preparation. Debris should be sufficiently burned so that it does not interfere with reforestation or range use and meets hazard abatement requirements. The undisturbed ashes from debris piles are too concentrated and alkaline for establishment of most trees. When they are spread out over the landing, however, they usually enhance seedling growth by contributing valuable nutrients.

c. Items 2.3.1a and b. do not apply on poor and low sites and where the landings are 0.1 ha and 1% of the block area.

d. Where it was not feasible to save the topsoil (see 2.3.2a), the landing should be seeded with a mix containing a high legume content to help replenish the organic matter and nitrogen content of the soil.

e. Prior to the next breakup, measures should be taken to prevent landing erosion, including:

   - grass seeding where erosion hazard is moderate to extreme (Table 2) (also benefits range and aesthetic values);
   - establishing sufficient drainage to prevent ponding; and
   - providing cross drainage to prevent water from flowing onto the landing.

f. Special measures should be taken where it is not possible to establish cross drains prior to the next breakup on winter-logged cut-blocks adjacent to sensitive fish habitat or domestic water supplies. Landings should be constructed to ensure the feasibility of drainage restoration on frozen ground (e.g., fill cross drains with logs or snow prior to freezing-in). Additionally, these areas should be patrolled by the licensee during the spring freshet to ensure that natural drainage patterns are maintained.

A PILOT STUDY OF SOIL COMPACTION ON SKID TRAILS AND LANDINGS IN THE PRINCE GEORGE FOREST REGION

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1 INTRODUCTION

Since the development of the "Guidelines for Harvesting Sensitive Slopes", issued as Standard Operating Procedure 4-2 by the Prince George Regional Manager,[1] many district and licensee staff in the Prince George Forest Region have focused attention on sites that should be cable logged according to the guidelines. Often these guidelines have been ignored by licensees claiming that these slopes can be harvested using conventional ground-skidding systems. Consequently, there have been few attempts to introduce alternative systems in the Prince George Forest Region.

Several studies have expressed concern over the excessive soil disturbances that result from ground-skidding operations in the interior of British Columbia.[2,3,4] As a result of these studies, the B.C. Ministry of Forests and Lands has attempted to produce guidelines that define the amount of disturbance that is acceptable upon logging.[5,6] Those guidelines are usually defined on an area disturbed/unit logged basis.

The steep slope guidelines identify sites requiring alternative harvesting systems, but do not suggest the amount of disturbance that is acceptable.[7] In order to quantify and give strength to the steep slope guidelines, the Ministry would like to develop acceptable disturbance classes for various sites in the Region. The limits for these classes would be the amount of soil disturbance that is unacceptable. If guidelines are to include acceptable disturbance limits, methods need to be in place which allow personnel to assess site disturbance consistently.

For conventional ground skidding, soil disturbance from the construction and use of skid trails and landings may be unacceptable because of reductions in site productivity. To develop estimates of what portions of skid trails and landings can be considered degraded landbase, a good understanding is required of the soil processes active on skid trails and of how these processes affect seedling performance. Previous studies have shown that soil bulk densities in the range of 1.2 to 1.5 g cm^{-3} will affect root development and result in at least 50% reduction in tree volume growing over a rotation (Russell 1973; DeYoe 1982[8]). Evidence also indicates that soil compaction is not significantly ameliorated over a rotation (Froehlich 1979). Using these bulk density limits, it may be possible to investigate the suggestion in the McBride Forest District that regeneration and growth are at acceptable levels on skid trails.[9]

In order to look at soil compaction on skid trails and landings in the Prince George Forest Region, a pilot study of bulk densities on these areas was initiated. The aim of the study was to determine which sections of skid trails and landings could be considered as lost land base, i.e., land so degraded that it cannot produce a merchantable crop of trees within the defined rotation age.

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[9] Bartlett, J., Forester, Zeidler Forest Industries Ltd., McBride, B.C.

2 SKID TRAIL STUDY

2.1 Methods

Five skid trails were randomly selected and sampled on each of four different clearcuts (n=20). Each skid trail was split up into components representing the berm, tracks, between track, sidecut and undisturbed portions of the cutblock adjacent to the skid trail (Fig. 1). Not all components are necessarily present on all skid trails sampled (i.e., sidecasts were not present on any of the skid trails sampled in this study). The part of the skid trail actually measured on each cutblock is shown in Table 1. Bulk densities were determined with a nuclear densiometer at 10, 20, and 30 cm depths at each sample point. The bulk densities shown in Table 1 are for the total soil, including stones. Relevant logging history, soil and terrain information, and other site data are shown also in Table 1.

2.2 Results and Trends

Bulk density results for each skid trail are shown in Table 1. For the summer skid trails, the data indicated that the sidecut, track, and between-track areas had bulk densities of 1.2 gm cm^{-3} or higher at depths greater than 10 cm, for all blocks except Small River. For the purpose of this report, unacceptable soil disturbance is considered to have occurred when bulk densities are increased to 1.4 gm cm^{-3} or greater or when C horizon material is exposed. According to a local industrial forester, the lower bulk densities observed across the Small River skid trail were likely a reflection of the very dry soil conditions when that cutblock was harvested.[9] For this previous statement to be valid, one must assume that the increase in bulk densities on skid trails was caused by mechanical compaction. Another possible explanation for the lower bulk densities observed across the Small River skid trail could simply be the result of soil displacement and exposure of naturally denser soil horizons.

The only winter skid trail sampled had bulk densities of less than 1.4 gm cm^{-3}, at depths greater than 10 cm, right across the trail. This indicates that even in the track portions soil compaction may be minimal on winter skid trails.

2.3 Recommendations

The results of the present study appear to confirm work by Smith and Wass (1979) that the sidecut, track and between-track portion of skid trails constructed during the summer months are likely to be unsuitable for growing trees. Bulk densities observed at these points are large enough that it is doubtful if any seedlings on these sites could grow to a merchantable stem over the rotation lengths scheduled.

Using an average of 7.8 m for the width of summer skid trails from the top of the sidecut to the bottom of the sidecast (Smith and Wass 1979), one could assume that 4.5 m of this distance is unsuitable for good tree growth. From the trends observed in this study, it may be best not to encourage planting on these sites. Rather, these skid trails could be viewed as part of the permanent land base given over to road transportation and, as such, would then be reused at the end of the next rotation.

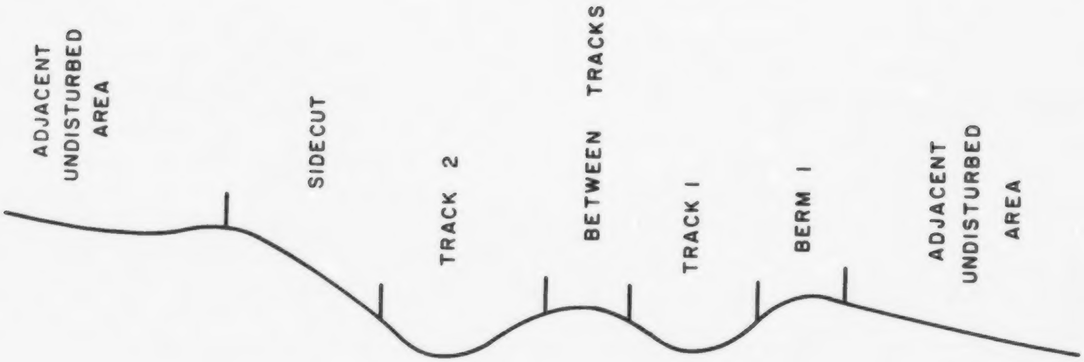
ADJACENT UNDISTURBED AREA
SIDECUT
TRACK 2
BETWEEN TRACKS
TRACK I
BERM I
ADJACENT UNDISTURBED AREA

FIGURE 1. Skid trail components.

TABLE 1. Logging, site and bulk density information for skid trails

Name of Cutblock	Subzone	Forest District	Year of Logging	Season of Logging	Soil Texture	Terrain Unit	% Slope	Depth (cm)	Bulk Density (g cm^{-3}) Adjacent Undisturbed Area	Berm 1	Track 1	Between Tracks	Track 2	Sidecut
Vama Vama 1	SBSj1	P.G.East	1978	Summer	SiL	Morainal	20	10	.9	--	1.3	1.7	1.5	--
								20	1.2	--	1.45	1.65	1.7	--
								30	1.35	--	1.5	1.75	1.65	--
Vama Vama 2	SBSj1	P.G. East	1979	Summer	SiL-SiCL	Morainal	20	10	.6	1.4	1.6	1.20	1.3	.9
								20	.9	1.6	1.7	1.35	1.4	1.25
								30	1.15	1.5	1.8	1.4	1.6	1.4
Beaver	ESSFo	McBride	1979	Winter	SiL-SiCL	Fluvial over Morainal	45	10	.4	.5	.9	.55	.4	--
								20	.5	.8	1.1	.8	.8	--
								30	.3	.85	1.3	1.0	.9	--
Beaver	ICHj	McBride	1977	Summer	SL	Morainal	10	10	1.1	1.15	1.3	1.1	1.1	1.1
								20	1.25	1.2	1.5	1.25	1.3	1.3
								30	1.25	1.3	1.6	1.35	1.5	1.7
Small River	SBSh	McBride	1981	Summer	SL	Morainal	45	10	.4	.4	1.1	1.0	1.3	1.3
								20	.6	.5	1.15	1.25	1.6	1.4
								30	.7	.4	1.15	1.35	1.8	1.4

TABLE 2. Logging, site and bulk density information for landings

Name of Cutblock	Subzone	Forest District	Year of Logging	Season of Logging	Soil Texture	Terrain Unit	Bulk Density (g cm^{-3}) Undisturbed Area Measurements 10 cm Depth	Undisturbed Area Measurements 20 cm Depth	Undisturbed Area Measurements 30 cm Depth	Portion of Landing Sampled	Landing Measurements 10 cm Depth	Landing Measurements 20 cm Depth	Landing Measurements 30 cm Depth
CP50-CB5	SBSo	Mackenzie	1977	Summer	SiL	Morainal	.75	1.15	1.35	--	1.7	1.95	2.1
CP51-CB31	SBSo	Mackenzie	1978	Summer	SiL	Morainal	.44	.8	1.0	--	1.4	1.75	1.85
Scobel Block	SBSo	Mackenzie	1974	Winter	SL-S	Fluvial	--	--	--	--	1.1	1.4	1.6
Vama Vama	SBSj1	P.G. East	1979	Summer	L	Morainal	--	--	--	--	1.6	1.8	1.9
Phillips CB1	SBSj2	Mackenzie	1977-78	Winter	SiL	Morainal	1.05	.7	.9	fill part	1.6	1.7	1.8
										sidecut	1.65	1.75	1.25
CB206	SBSj2	Mackenzie	1982	Winter	SL-S	Fluvial	.6	.9	1.1	--	.9	1.25	1.35

3 LANDING STUDY

3.1 Methods

Six landings were randomly chosen, and on each landing, one sample point was randomly located. Bulk densities were determined at the 10, 20, and 30 cm depths (Table 2). One sample point was also randomly located near each landing in the undisturbed part of the cutover. On one winter landing (Phillips), two holes were drilled for sampling: one in the fill section of the landing and the other in the sidecut section. Logging histories, location, and soil and terrain information for each landing are shown also in Table 2.

3.2 Results and Trends

The data indicated that all the summer landings sampled had bulk densities greater than 1.6 g cm^{-3} at depths below 10 cm (Table 2). Winter landing bulk densities were lower than summer landing bulk densities but still greater than 1.4 g cm^{-3} at depths below 10 cm except for the CB206 landing and the sidecut portion of the Phillips CB1 landing (Table 2). The bulk densities of the undisturbed areas on each cutover were below 1.2 g cm^{-3} except at the 30 cm depth on CP50-CB5. These results indicated that severe soil compaction had occurred on all landings, summer and winter.

3.3 Recommendations

The results of this study indicate that, unless rehabilitation occurs, landings should not be planted because the bulk densities of these sites are so high that root growth would be severely restricted. A study recently concluded that landing rehabilitation may be too expensive for the benefits derived.[10] There is obviously an urgent need to reduce the areal extent of landings, thus reducing disturbances due to landings.

4 CONCLUSIONS

From the results of this pilot study, it seems likely that the use of conventional ground-skidding systems on most of our forest sites in the Prince George Forest Region is causing a significant loss of productive land base to the use of skid trails and landings. To help reduce soil disturbance on steep slopes in the Prince George Forest Region, disturbance guidelines should be established for varying slopes and/or soil conditions. This report is a first step towards detailed studies that could help create such guidelines.

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[10] W.W. Carr, Consultant, Terrasol Consulting Ltd., Vancouver, B.C.

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A PILOT STUDY OF THE AMOUNT OF SOIL DISTURBANCE ON SELECTED CUTOVERS IN THE PRINCE GEORGE FOREST REGION

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1 INTRODUCTION

Concern over excessive soil disturbance that often results from ground-skidding operations in the interior of British Columbia has been expressed by several authors.[1,2,3] As a result, the B.C. Ministry of Forests and Lands has attempted to produce guidelines that define acceptable disturbance during forest harvesting.[4,5] These guidelines have usually been defined on an area disturbed/unit logged basis.

McLeod (1988) defined unacceptable disturbance in the Prince George Region to be the exposure of C-horizon material or when soil compaction is such that the total soil bulk density exceeds 1.4 g cm^{-3}. In an initial pilot study in the Prince George Region, McLeod (1988) found that landings and the sidecut, track, and between-track portions of skid trails were areas where unacceptable disturbance had occurred. It was concluded that these areas were unsuitable for growing merchantable stems over the next rotation.

Steep slope guidelines help identify sites that require alternative harvesting systems, but they do not define the amount of disturbance that is acceptable during harvesting.[5] In order to give strength to the steep slope guidelines, the Ministry would like to develop acceptable disturbance limits for the slope classes defined in SOP 4-2.[6] The upper limits for disturbance would be that amount of soil disturbance that is unacceptable.

Before preparing guidelines that state acceptable disturbance limits, the amount of site loss that presently occurs as a result of current harvesting strategies must be determined. A pilot study was, therefore, initiated to determine the amount of disturbance that occurs on various slopes as a result of road, landing and skid trail construction and use.

2 METHODS

Six cutblocks were selected in the Prince George Forest Region to represent a variety of slope classes and terrain types, both summer and winter logging, and normal ground-skidding operations. Details of the cutblocks are given in Table 1. For each harvested cutblock, black and white air photographs were obtained. The scale of these photographs varied between cutblocks (Table 2). From these air photos, topographic maps of each cutblock, with 10-m form lines at a scale of 1:5000, were produced and formed the data base for this pilot study. All cutblock boundaries, skid trails, landings, roads, and slope breaks within the cutblock were delineated on the maps. The cutblocks were split into slope classes of 0-30, 31-40, 41-55, and 56+ %, the same classes that were used in SOP 4-2.

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[4] B.C. Ministry of Forests, Planning Branch. 1983. Maintenance of productive capability of forest land. Victoria, B.C. Draft proposal. 4 p.

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[6] Ibid.

TABLE 1. Logging history, slope and terrain classification for cutblocks in the study

Cutblock	Cutting Permit	Size (ha)	Year of Logging	Season of Logging	Subzone	Slope Range (%)	Parent Material
Towkuh Creek	A07789	431	1977	S	SBSj	0-55	Morainal
Kiwa Creek 1	A03001	53	1971-73	W	ESSFo	0-55	Morainal
Kiwa Creek 2	N/A	295	N/A	W	ESSFo	0-56+	Morainal
McLean & Twidwell	A01230	61	1973-74	S	BWBSd	0-56+	Morainal
Holmes River	A01155	121	1974	S	ESSFo	0-56+	Morainal
Slender Lake	A08577	113	1977-78	S&W	SBSj	0-55	Morainal

TABLE 2. Scale of air photos used in the study

Cutblock Name	Photographic Scale
Towkuh Creek	1:15840
Kiwa Creek 1	1:15840
Kiwa Creek 2	1:15840
McLean & Twidwell	1:20000
Holmes River	1:15840
Slender Lake	1:40000

A planimeter was used to measure the area of landings and cutblocks. If a main road crossed a landing, the area of the main road contained within the boundary of the landing was deleted from the landing area (after McMorland 1980). The width of disturbance for main roads was taken to be 10 m (McMorland 1980), while disturbance widths for skid trails were derived from McMorland (1980) and are shown in Table 3.

For each cutblock and each slope class on the cutblock, total area, and area of roads, landings, and skid trails was estimated. To estimate the areas of main roads and skid trails, their lengths were multiplied by the relevant width.

TABLE 3. Width of skid trail sections used in this study

Slope Classes (%)	Cutbank Width (m)	Surface Width (m)	Total Width (m)
0-30	0.5	2	2.5
31-40	0.5	1.9	2.4
41-55	0.7	1.9	2.6
56+	0.6	1.9	2.5

3 RESULTS AND DISCUSSION

On cutblocks harvested during the summer, 17-19% of the land base was affected by the combination of landing, main road, and skid trail construction (Table 4). On winter-logged cutblocks, the land base affected was between 12 and 18%. Soil disturbance from main roads was generally low on steeper slopes. This is because main road construction is usually restricted to slopes less than 30%. Where roads occurred on slopes over 30%, there was less land base used as skid trails, but the proportion disturbed by these skid trails was still approximately 20%. On the two blocks that were winter logged only (Kiwa Creek 1 and 2), the area in main roads was considerably less than that on the blocks that were summer logged. McLeod (1988) found that winter-logged skid trails were not compacted, but it now appears that the sample size used was too small to make any firm conclusion. The degree of compaction on winter skid roads needs to be studied.

Landings were located primarily on slopes less than 30%. Landings are generally restricted to the less steep ground that is economically accessible by the main haul road. Skid trails are then constructed on the steeper slopes to make the standing timber accessible. This is reflected in the results in that, on all blocks, skid trails accounted for an increasing proportion of the area as the slope increased, regardless of season of logging. Similar results were found by Smith and Wass (1976). On slopes greater than 40%, between 16 and 26% of the cutblocks were covered by skid trails. To reduce disturbance on these steep slopes, managers could utilize harvesting systems that do not create skid trails, or adopt the concept of designated skid trails to increase the distance between skidroads and rely on the loggers to pull more line (Bradshaw 1979). That is, conventional harvesting systems will likely be either replaced with alternative systems (i.e., cable operations) or substantially modified. No cutblock in the present study contained extensive areas of very steep slopes (>56%). Many of these steep slopes are difficult to harvest using conventional equipment and have been left to the second pass.

Alternative harvesting systems to be recommended for these steep slopes need to be analysed from an economic standpoint. Any increased costs of logging, however, must be balanced against the decreased loss of productive land, because of a reduction in skid trail development.

The conclusion of Smith and Wass (1979) that conventional summer-harvested cutblocks had unacceptable disturbance is valid for the cutblocks examined in this study. When compared to summer-harvested cutblocks, areas that have a good snowpack (winter-harvested cutblocks) did not have as much unacceptable disturbance.

4 IMPLICATION OF THE STUDY FOR THE MINISTRY OF FORESTS AND LANDS

This study and the results in McLeod (1988) indicate that the use of conventional harvesting systems on steep slopes, especially during the summer, may cause unacceptable loss of forest land; i.e., the sites will not produce timber at their undisturbed potential over the scheduled rotation. Current harvesting is largely concentrated on the gentle slopes (less than 30%). As these sites are harvested, logging operations will concentrate on the remaining, steeper slopes.

Current management practices may have already had an detrimental impact on the annual allowable cut. While skid trails and landings may be part of the transportation network when the next rotation is harvested, it is difficult to ignore the implication of significantly reducing the productivity of up to 20% of the land base each time a site is harvested. While it may not be cost-effective to rehabilitate skid trails, there is no support for the expectation that these sites will eventually come back into production over a reasonable time (Froehlich 1979). It would seem to be more prudent to reduce setting, landing and skidroad disturbance on cutblocks. The steep slope guidelines for the Prince George Region clearly indicate options that will reduce serious disturbance during the logging of steep slopes. To not adopt these guidelines will result in continued degradation of the land base from which the annual allowable cut is determined.

TABLE 4. Area disturbed by roads, landings and skid trails for various slope classes in each cutblock in the study

Slope Class	Season of Logging	Total Area (ha)	Landings (ha)	Main Roads (ha)	Skidroads (ha)	% of Area in Landings	% of Area in Main Roads	% of Area in Skid Trails
McLean and Twidwell Creeks								
0-30	S	40.34	1.45	1.54	2.43	3.6	3.8	6.0
31-40	S	3.93	.22	.11	.52	5.6	2.8	13.2
41-55	S	9.40	0	.15	2.39	0	1.6	25.4
56+	S	7.50	.04	.53	1.86	.5	7.1	24.8
Total Area		61.17	1.71	2.33	7.2			
Whole Cutblock						2.8	3.8	11.8
Holmes River								
0-30	S	55.26	2.38	1.74	5.45	4.3	3.1	9.9
31-40	S	26.13	0	0	4.17	0	0	16.0
41-55	S	34.28	0	0	5.39	0	0	15.7
56+	S	3.72	0	0	.73	0	0	19.6
variable	S	1.38	0	0	.4	0	0	
Total Area		120.77	2.38	1.74	16.14			
Whole Cutblock						2.3	1.9	13.4
Slender Lake								
0-30	W	82.65	8.51	3.25	3.04	10.3	3.9	3.7
31-40	S	15.14	.11	.12	1.12	.7	.8	7.4
41-55	S	12.9	.06	.78	1.78	.5	.6	13.8
56+	S	1.78	0	0	.33	0	0	18.5
Total Area		112.47	8.68	4.15	6.27			
Whole Cutblock						7.7	3.7	5.6
Towkuh Creek								
0-30	S	406.55	28.46	21.17	26.94	7.0	5.2	6.6
31-40	S	10.58	.18	.36	1.75	1.7	3.4	16.5
41-55	S	13.63	.27	.15	2.24	2.0	1.1	16.4
56+	S	0	0	0	0	0	0	0
Total Area		430.76	28.91	21.68	30.93			
Whole Cutblock						6.7	5.0	7.2
Kiwa Creek 1								
0-30	W	27.28	.89	.13	2.93	3.3	.5	10.7
31-40	W	15.57	0	0	2.95	0	0	19.0
41-55	W	7.35	0	0	1.52	0	0	20.7
56+	W	1.47	0	0	.18	0	0	12.2
variable		.95	.95	0	0	100	0	0
Total Area		52.62	1.84	.13	7.58			
Whole Cutblock						3.5	.3	14.4
Kiwa Creek 2								
0-30	W	118.69	4.22	1.21	8.09	3.6	1.0	6.8
31-40	W	105.60	0	0	13.72	0	0	13.0
41-55	W	51.04	0	0	6.91	0	0	13.5
56+	W	19.86	0	0	2.92	0	0	14.7
Total Area		295.19	4.22	1.21	31.64			
Whole Cutblock						1.4	.4	10.7

If the Ministry is to implement new harvesting guidelines, there needs to be good communication between industry and government so that licensees understand the reasons for the changes. The Ministry may need to provide incentives to encourage contractors with special skills, such as cable operators, to operate on a full-time basis in the Region. This would mean that both summer and winter cable operations could be established. Finally, there needs to be a cost-benefit study that would quantify the impact of continuing soil degradation on the forest industry. Once this study has been completed, acceptable disturbance limits may be recommended for the various slope classes.

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A PROCEDURE FOR QUANTIFYING THE VOLUME LOSS ASSOCIATED WITH DEGRADED AREAS AND TRANSITION ZONES IN THE PRINCE GEORGE FOREST REGION

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Studies have shown that skid trails alone can cover 25-30% of a harvested area (Steinbrenner and Gessel 1955; Froehlich 1973). Even higher percentages of a harvested area can be affected if landings and main roads are included. Studies conducted in the Prince George Forest Region have confirmed that up to 20% of harvested areas can be degraded and can be considered lost from the productive land base (McLeod 1988; McLeod and Hoffmann 1988). Unacceptable disturbance was defined in these studies as exposure of C-horizon material or when soil compaction was such that the bulk density exceeded 1.4 g cm^{-3} (McLeod 1988). These reports concluded that the sidecut, between-track, and track portions of skid trails, main roads, and landings could all be considered degraded and probably not able to support merchantable stems over an expected rotation length. Thus, a manager could consider omitting these degraded areas from the land base estimate used in calculating future yields from harvested areas. One method of calculating volume loss on degraded areas is to use the MAI (mean annual increment) estimate for the cutting unit and multiply this value by the area of degraded land. The resulting value would give a manager a quick estimate of forest productivity loss on the harvested area that resulted from logging activities. However, eliminating degraded areas and the corresponding potential harvestable volumes from the land base used to calculate annual allowable cut does not fully recognize the potential harvestable wood volume that would be lost on a cut block. There is evidence that land adjacent to these degraded areas (transition zone) experiences volume losses that can further reduce potential harvestable volumes (Wert and Thomas 1981). Transition zone is defined to encompass an area 3 m in width and lying adjacent to degraded land.

The objective of this report is to outline a procedure which would enable managers to quantify the volume loss associated with the degraded area and transition zone on cutblocks in the Prince George Forest Region. This report will separate the potential harvestable volume impacts associated with the transition zone from the potential harvestable volume losses associated with degraded areas, and concentrate on developing a guideline for estimating the potential harvestable volume loss on the cutblocks' productive land base. For the purpose of this report, productive land base will be defined as the total cutblock land base minus the degraded area contained within the cutblock boundaries.

In order to quantify the potential harvestable volume impact, managers would like to have a good understanding about how the tree interacts with site and soil factors under the local climatic conditions. Often this information is not available, so managers resort to the use of guidelines that try to estimate the magnitude of the resulting volume loss on the cutblock's productive land base from the modification of the tree rooting pattern, the reduction of tree root volumes and the growth reductions stemming from fewer nutrients being available.

A study conducted by Wert and Thomas (1981) measured the effects of tractor logging that occurred in 1947 upon the productivity of a subsequent natural stand of Douglas-fir, and assessed the degree and extent of residual soil compaction. This study showed that:

a) there was a 11.8% volume loss prorated over the entire harvested area;

b) 10% of the harvested area was occupied by skid trails that produced 34.1 m^3 ha^{-1} of merchantable timber;

c) 8% of the harvested area was considered a transition zone;

d) the transition zone produced 97.2 m^3 ha^{-1} of merchantable timber; and

e) the remaining 82% of the harvestable area produced 128.9 m^3 ha^{-1} of merchantable timber.

The skid trails sampled by Wert and Thomas were likely unbladed structures (i.e., humus and the top 20 cm of mineral soil are not removed). In the Prince George Forest Region, skid trails constructed on slopes over 30% are usually bladed structures (i.e., humus and the top 20 cm of mineral soil are removed from the track, between-track, and sidecut portion of the skid trail). McLeod (in press) concluded that the sidecut, track and between-track portion of bladed skid trails are degraded areas unable to grow a merchantable tree. The reasons for these areas becoming degraded could be due to increases in bulk densities that were observed associated with these portions of bladed skid trails, the removal of the upper 25 cm of soil material and the minimal nutrient level in the exposed C horizon (McLeod [in press]). While Wert and Thomas measured a 74% volume reduction on unbladed skid trails, volume reductions on bladed skid trails in the Prince George Forest Region are assumed to be 100%.

The transition zone identified by Wert and Thomas, showed a 24.6% reduction in volume. Despite the fact that the transition zone volume losses observed by Wert and Thomas occurred in conjunction with a crawler tractor operation, the magnitude of the loss could be assumed to represent the volume losses incurred in transition zones on cutovers in the Prince George Forest Region. Also the proportion of transition zone to skid trail disturbance could be assumed to apply to cutovers in the Prince George Forest Region. In the Wert and Thomas study, for every 1% of cutover area covered by skid trails, 0.8% of the cutover area would be classified as a transition zone.

One procedure that could be adopted correlates the percent disturbance by selected slope classes observed by McLeod and Hoffman (in press) with the corresponding volume loss found on cutovers in the Prince George Forest Region, using Wert and Thomas skid trail-transition zone proportions and transition zone volume loss. The values obtained from using this procedure are shown in Table 1.

Managers must be very cautious about extrapolating results found by Wertand Thomas to conditions in the Prince George Forest Region. However, even if this study does not have direct application to conditions in this region, it nevertheless represents the best information available for Prince George managers to utilize in their efforts to assess the impact that ground-skidding operations are having on the future productivity of their land base. We need to conduct research like that outlined by Wert and Thomas if we wish to get a better estimate of the volume losses being incurred from ground-skidding operations in the Prince George Forest

TABLE 1. Volume loss on harvested areas in the Prince George Region by selected slope classes (based on a study reported in McLeod and Hoffmann [in press])

Slope Class (%)	Season of Logging	Degraded Area (%)		Volume Loss (% ha^{-1})	Transition Zone (%)		Volume Loss (% ha^{-1})
		Mean	Range		Mean	Range	
0-30	S	7.5	6.0 - 9.9	100	6.0	4.8 - 7.9	24.6
	W	7.1	3.7 - 10.7	100	5.7	3.0 - 8.6	24.6
31-40	S	13.3	7.4 - 16.5	100	10.6	5.9 - 13.2	24.6
	W	16.0	13.0 - 19.0	100	12.8	10.4 - 15.2	24.6
41-55	S	17.8	13.8 - 25.4	100	14.2	11.0 - 20.3	24.6
	W	17.1	13.5 - 20.5	100	13.7	10.8 - 16.6	24.6
56+	S	21.0	18.5 - 24.8	100	16.8	14.8 - 19.8	24.6
	W	13.5	12.2 - 14.7	100	10.8	9.8 - 11.8	24.6
0-56+	S	10.8	7.2 - 13.4	100	8.6	5.8 - 10.7	24.6
	W	12.6	10.7 - 14.4	100	10.1	8.6 - 11.5	24.6

Region. Also, planners will need to continue to examine what impact existing levels of disturbance are having on the future productivity of forests (Annual Allowable Cut) and the long term sustainable yields associated with Timber Supply Areas in the Prince George Region. Policy needs to be developed that will ensure the reduction of detrimental site disturbance to acceptable target levels (see Table 2), especially as the future harvesting areas will include significant amounts of steep slopes.

TABLE 2. Acceptable levels (%) of soil disturbance for various slope classes (Hammond 1982)

Slope Class	Skid Road (Hammond) 1	Skid Road (McLeod & Hoffman) 2	Main & Spur Haul Roads (Hammond) 3	Landings (Hammond) 4	Total A[a] (using Hammond criteria)	Total B[b] (using McLeod criteria)
0-20	1	1	3	2.5	6.5	6.5
20-40	9	5	4	2	15	11
41+	14	8	5.5	2	21.5	15.5
0-41+	8	5	4	2	14	11

[a] Total A represents the totals of adding the values in columns 1,3 and 4.

[b] Total B represents the totals of adding the values in columns 2,3 and 4.

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SAMPLING SOME PHYSICAL CONDITIONS OF SURFACE SOILS IN THE FIELD[1]

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ABSTRACT

Guidelines for sampling some physical conditions of surface soils are described and field applications are provided. Following these guidelines allows soil scientists to make estimates of the area of any surface soil condition of interest (e.g., compaction, displacement, puddling, etc.) and make statements regarding the precision of those estimates. This was not possible with previously used sampling systems. Statistical tests can be performed to determine if soil resource objectives established for individual management activities have been met or exceeded.

Field data are analyzed by hand or by computer. Computer analysis is rapid and provides unit summaries, as well as transect by transect summaries. Confidence intervals around each of the estimates are computed and displayed. User response to the presentation of soils information in this format has been positive. Use of sampling guidelines has provided USDA Forest Service land managers with useful and reliable information. The feasibility of achieving soil management objectives and reliability of standards are being evaluated.

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[1] This presentation was previously given at the 6th North American Forest Soils Conference held in Knoxville, TN. This abstract was published in the proceedings of that conference.

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EFFECTS OF PRESCRIBED BURNING ON FOREST PRODUCTIVITY OF SOME COASTAL BRITISH COLUMBIA SITES

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ABSTRACT

The objectives of this project are to determine the effects of prescribed burning on tree growth during plantation establishment, and to begin long-term monitoring of the impact of fire on forest productivity and site nutrient status. Of particular interest is the amount of surface organic matter consumption from fires of various intensities. This abstract briefly outlines the objectives and experimental design, and presents some initial results from the measurement of fire impacts.

The three study sites are in Sproat Lake Woodlands Division of MacMillan Bloedel Limited, west of Port Alberni, B.C. All are within the Coastal Western Hemlock biogeoclimatic zone, wetter maritime subzone. The sites are south- to southeast-facing slopes between 450 and 650 m in elevation, and support similar ecosystem associations. Slash and brush (mainly salal) are such that site preparation is needed on most of the area in order to obtain a fully stocked plantation.

The treatments are replicated using a balanced incomplete block design. Two replicates of two prescribed fire treatments and controls (unburned) were allocated to the three sites so that one site has both fire treatments and the two others each have a fire treatment and a control.

Pre- and post-fire conditions were measured for the four burns and two controls during 1985. Two "low impact" burns were accomplished in May, and two "high impact" burns in late September and early October. Sprinkler lines were used extensively to control the perimeter of the fires in order to obtain unburned areas immediately adjacent to the burns. Several spring plots burned during the adjacent fall burn on one of the three sites; however, monitoring of the reburned areas produced some unique data.

Data analysis of fire impacts is underway. The amount of mineral soil exposure illustrates the difference in impacts between the spring and fall burns. Pre-fire mineral soil exposure ranged from 0 to 9% on all areas. Post-fire exposure ranged from 0 to 10% for the spring burns, and from 13 to 57% and 59 to 90% on the two fall burns.

Consumption of woody fuels and surface organic (duff) layers was also compared. The spring burns consumed 71-87% of the woody fuels under 7 cm in diameter, while the fall burns consumed 87-91% in the same size class. Average duff consumption for the two spring burns was 24 and 40%; consumption for the two fall burns was 61 and 85%.

Low-level air photos were obtained before and after burning to prepare detailed maps of the study areas and fire boundaries on a 1:1000 topographic base. These maps will facilitate plot location for long-term monitoring.

The B.C. Ministry of Forests and Lands is monitoring understory vegetation growth to determine the impact of different seasons and intensities of prescribed burns on wildlife forage production. These data, along with data from the vegetation coverage plots in the study, should provide valuable information from a vegetation management perspective.

All sites were planted in spring 1986 with Douglas-fir, western redcedar, and yellow-cedar. Tree growth, vegetation coverage, and soil nutrients will be monitored for five years.

The study is jointly funded by MacMillan Bloedel Limited and the Canadian Forestry Service through the Unsolicited Proposals Program of the Department of Supply and Services Canada. The initial funding will continue until 1991. The need for long-term monitoring of plots will be determined when the initial project is completed. Further information can be obtained by contacting the author.

LANDSLIDE REHABILITATION AND EROSION CONTROL IN THE QUEEN CHARLOTTE ISLANDS

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ABSTRACT

Landslides are a concern of land managers on the British Columbia coast because of soil erosion, site productivity losses, and potential adverse impacts on fish streams. A project is underway in the Queen Charlotte Islands to test methods of landslide rehabilitation for controlling surface erosion and stream sedimentation, and for establishing conifers. Several native shrub species and two planting designs are being tested in combination with hydroseeding of grasses and legumes. This abstract outlines the objectives and design of the project, and presents some results from year 2 of this 5-year project.

The project includes two separate trials. Trial 1 compares the effects of two treatments on plantation success: (1) hydroseeding alone, and (2) shrubs (Sitka alder) planted in two patterns - 1 x 1 m spacing versus 30 cm spacing in rows 4 m apart. Trial 2 compares the performance of six native shrubs as stabilizers of landslides: hardhack, honeysuckle, salmonberry, Sitka alder, thimbleberry, and willow. Both trials are planted with Sitka spruce at 2 x 2 m spacing.

In Trial 1, Sitka spruce survival was 92% after two growing seasons. Deer browsing was severe in the first year, but was generally light to moderate in the second year.

Seedlings in heavy grass cover were browsed less than those in more exposed areas. The benefits of the grass and legume cover for surface stabilization and moisture retention appear to outweigh any competitive influence on the spruce at this stage. It is too early to assess the merits of the shrub plantings. The Sitka alder ranges in height from 2 to 27 cm; nearly all have been browsed heavily.

The species performance trial showed significant differences in survival between the various shrubs. Salmonberry and Sitka alder had the best survival at 87 and 76%, respectively. Thimbleberry (4%) and willow (24%) had the poorest survival. Height growth of surviving plants was similar for all species. Browsing was heaviest on Sitka alder and honeysuckle.

The trials will be measured for three more growing seasons. Results will be used to prepare guidelines for operational landslide and roadcut rehabilitation. This project is funded in part under Section 88 of the Forest Act, as administered by the B.C. Ministry of Forests and Lands. Further information can be obtained by contacting the author.

SLASHBURNING EFFECTS ON TREE GROWTH AND NUTRIENT LEVELS AT MISSION TREE FARM: PROJECT STATUS

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ABSTRACT

Preliminary results and project status are summarized for studies initiated in spring, 1984. The initial objectives of the study were to (1) estimate the effect of slashburning on the growth and plots established by the Canadian Forestry Service (CFS) in 1968-70 at Mission Tree Farm; and (2) explore fire effects on soil mineralizable nitrogen. Based on preliminary results and, to take advantage of unique opportunities provided by an adjacent slashburn planned for fall 1985, the study has been expanded to (3) permit further sampling of the old CFS plots; (4) monitor effects of the new slashburn on soils adjacent to two previous CFS plots; and (5) allow growth chamber study of slashburning effects on mycorrhizal associations in Douglas-fir, western hemlock and western redcedar, using soils from this study and concurrent research on Vancouver Island. Trends are apparent for Douglas-fir, western hemlock, western redcedar, and amabilis fir growth among the various fire treatment plots, with Douglas-fir appearing to benefit from the prescribed burning, while the others benefit little or at all. Growth and foliar nutrient data for Douglas-fir and western hemlock appear related to fire impact data (e.g., slash consumption). A number of nutrients (e.g., P, K, Fe, Zn, B) are possibly deficient in Douglas-fir on a number of the treatment plots, with burning appearing to aggravate some of these conditions. Interpretation of final results will be aided by further data collection, data analysis, data from the new burn, the mycorrhizal study, concurrent research, and studies of fire effects on competing vegetation.

1 INTRODUCTION

Prescribed fire is a common site preparation tool in British Columbia. Although it is often beneficial for the early stages of regeneration, longer-term effects on tree growth and site nutrient levels have not been extensively studied. Many factors affect tree growth and nutrition; these in turn may each be affected by slashburning in a different (i.e., positive or negative) way (Table 1). Many anomalies exist in the literature reporting slashburning effects; Feller (1982a,b) noted that, for each effect reported, it is normally possible to find its opposite effect reported elsewhere. Dr. Ballard has summarized prescribed fire effects on the soil factors in the paper presented at this workshop. For all growth factors, the effects of fire impact may change over time and become more or less important.

The actual relationship between fire impact and site nutritional status may be altogether different than with tree growth, depending on which factors are the most growth-limiting. For example, Ballard (1985), on sites near Prince George, found better growth but poorer N status of planted spruce on burned sites, and ascribed the growth enhancement to improvement of the growth-limiting soil temperatures (Dobbs and McMinn 1977).

In coastal British Columbia, however, soil climate is not as limiting to growth and one may expect fire effects on nutrient limitations and competing vegetation to influence long-term site productivity.

The effects of burning may be expected to vary not only in space and with fire behavior, but also over time after burning. For example, Bråathe (1974) noted that in Norway the better short-term tree growth on burned sites was not necessarily sustained in the long-run, and cumulative height growth after about eight years was sometimes lower than on unburned sites.

TABLE 1. Simplified summary of short-term effects of slashburning on factors affecting tree growth and nutrition[a] (from Curran [in press, 1987.])

Type of Factor	Factor	Possible Effects of Burning	Possible Effects on Tree
DIRECT GROWTH FACTORS	Available Light	Increased (decreased shading)	Positive, maybe negative if S-facing slope or shade-requiring spp.
	Available Water	Decreased infiltrability, and forest floor (and usually upper soil) water-holding capacity	Negative if serious summer drought on tree micro-site
		Increased in receiving areas	Positive if not excessive
	Available Carbon Dioxide for Photosynthesis	Negligible?	Negligible?
	Temperature Regimes (air and soil)	Increased range above ground, at surface, and below ground	Positive if respiration decreased at night and/or soil temp. increase. Negative if too extreme for species (slope, aspect important)
		Decreased range at surface possible if mineral soil exposed	Positive if decreased heat stress on stem and/or increased heating of root environment Negative if frost heaving occurs
	Rooting Substrate	Decreased if erosional losses	Negative
		Decreased if species relies heavily on forest floor	Negative if significant forest floor losses occur
		Seedling frost-heaved due to temp. effects	Negative
		Increased if sediment gain	Positive if not excessive
	Soil pH	Increased up to 3 pH units due to ash	Positive if not excessive for species requirements or nutrition. Negative if excessive for species requirements or nutrition
	Soil Nutrients - Total Content	Decreased due to atmospheric losses, leaching and erosion	Negative if any nutrient pool falls below requirements

TABLE 1. (Continued)

Type of Factor	Factor	Possible Effects of Burning	Possible Effects on Tree
	Relative Availability of Remaining Nutrients	Increased for N, S, K, Ca, Mg due to rapid mineralization of organic matter by fire; and sometimes enhanced N fixation	Positive unless excessive supply of one nutrient antagonizes uptake of another (e.g., Ca induced Fe deficiency)
		Decreased for Fe, Mn, Zn, Cu because of effects of increased pH	Negative if any one falls to growth-limiting levels
		Increased for Mo because of effects of Increased pH	Positive if otherwise growth-limiting (little known)
		Increase or decrease for P, B depending on balance of pH, org. matter effects	Positive if increased Negative if decreased (e.g., P absorption by charcoal)
SOME INDIRECT GROWTH FACTORS	Soil Cation Exchange Capacity(CEC)	Increased pH-dependent CEC	Positive because of increased nutrient retention and soil buffering to change
		Decreased if excessive organic matter consumption	Negative because of decreased nutrient retention and soil buffering to change
	Competing Vegetation	Increased if propagation encouraged (e.g., salal roots not burned)	Negative because of increased competition
		Decreased if propagules consumed or discouraged	Positive
	Root Pathogens	Increased if propagation or growth encouraged (e.g., *Rhizina undulata* spore germination, growth encouraged by fire)	Negative
		Decreased if opposite effect (i.e., only if persistent deep burning of roots occur)	Positive
	Other Pathogens	Decreased if dependent on remaining slash (e.g., mistletoes)	Positive
		Increased if reduces antagonistic agents or encourages alternate host (e.g., *Ribes* for white pine blister rust)	Negative

TABLE 1. (Continued)

Type of Factor	**Factor**	**Possible Effects of Burning**	**Possible Effects on Tree**
	Wildlife Grazing	Increased	Negative if trees preferentially grazed Positive if brush preferentially grazed
		No change in grazing habits	No effect
	Mycorrhizae	Decreased if fungi or host discouraged	Generally considered negative
		Increased if fungi or host encouraged	Generally considered positive
	Beneficial Organisms (e.g., Earthworms)	Decreased in short term due to drastic change in environment and substrate	Negative unless recolonization rapid
	(e.g., Nitrogen fixing such as *Ceanothus* spp.)	May be increased	Positive due to increased N cycling unless N fixers are in competition with trees for resources

- Actual effects observed depend on site conditions, fire impact characteristics, tree species and growing stock, and actual factors limiting growth, (e.g., although nutrient levels may decline they might not reach growth limiting levels);
- Magnitude and duration of observed effects also vary with above; and
- Information comes from a number of references, well summarized by Feller (1982a,b) and Wells *et al.* (1979).

Recent research on growth disturbances (e.g., Carter *et al.* 1984) and micronutrient deficiencies (e.g., Majid 1984) has suggested a need for more thorough study of prescribed fire effects on micronutrient status. Even for the macronutrients, there is no clear relationship between slashburning and tree growth/nutrition. Although burning promotes volatilization and fly-ash losses of a number of essential plant nutrients, such as N (DeBell and Ralston 1970) or S (Allen 1964), and reduces total site nutrient capital, nutrient availability is not necessarily reduced. After burning, residual N, for example, may become more available (Mroz *et al.* 1980) or available nutrient levels may decline but not reach growth-limiting levels.

However, fire impact effects on the long-term availability of nutrients and the overall effects on site productivity remain poorly understood. This is due to the short-term nature of most past research, and also due to the incomplete documentation of fire impact on past research sites (Klock and Grier 1979). While a number of detailed fire research trials have been recently initiated (e.g., Beese 1984, 1986; Curran *et al.* 1986a; Hawkes [in press]), it will be many years before any indication of long-term effects will be apparent. In the meantime, some insight may be provided by study of past research sites (Curran 1988).

The above discussion indicates that foresters are still hard-pressed to predict the actual effects of a particular slashburn on long-term tree growth. Despite the usefulness of slashburning for fire hazard reduction and site preparation for planting, it is, difficult to know the long-term consequences of a particular fire prescription without long-term feedback provided by research. My research has been formulated to address this problem, and includes research sites in south coastal British Columbia that are described in Curran (1988), with some mention in my other paper at this workshop (Curran 1988).

The Canadian Forestry Service (CFS) prescribed fire research plots established at Mission Tree Farm in 1968-70 provide a unique opportunity for the short-term study of moderately "long-term" effects of slashburning and for the input of scientific feedback to current forest management, policy, and research. The overall objective of the research at Mission Tree Farm is to quantify the long-term effects of slashburning on tree growth and site nutrient levels. This will be accomplished by addressing a number of specific objectives: (1) quantifying tree growth and nutrient status; (2) quantifying soil nutrient status on selected micro-plots, in order to assess the feasibility of detailed soil studies on the CFS plots; (3) determining relationships between the tree/soil data and the CFS fire data; (4) monitoring fire impact and its effects on soils for a new slashburn adjacent to two of the CFS plots; (5) conducting a preliminary study of fire effects on nitrogen mineralization (M.J. Douglas, M.Sc. student, University of British Columbia); and (6) evaluating fire effects on initial mycorrhizal associations of Douglas-fir, western hemlock and western redcedar.

2 STUDY AREA

In 1968, CFS initiated a prescribed fire study in the Mission Tree Farm. The administrators of the TFL were the only volunteers willing to accept the risks of the severe burn conditions necessary for some of the planned experiments. The program included detailed monitoring of fire behavior, fire impact, and fire effect on plant succession and tree regeneration (Lafferty 1972). The fire physics data were instrumental in the development of prescribed burning application of the CFS Fire Weather Index (e.g., Muraro *et al.* 1973; Lafferty 1980; Canadian Forestry Service 1984). Two reports were prepared on the regeneration and plant succession study (Lafferty 1972, 1980). Twenty-two experimental burns were carried out, with eight of these permanently marked for ecological study (Lafferty 1972; K. King, Plant Ecologist, CFS, Pac. For. Cent., pers. comm., Victoria, B.C.). Four treatment plots (T6, T7, T8, T14) with two partial controls (C6, C7) were established at a lower elevation area; four treatments (T10 - T13) were established and two controls (C12, C13)at higher elevation (Fig. 1).

The treatment plots studied contain 25 permanently marked micro-plots in which fire impacts were measured. These micro-plots are very important for follow-up study because they identify specific points on the ground with known fire impact and enable detailed analyses of within-site fire effects. Micro-plots enable pairing of data on site conditions, treatment impact, and tree performance, to reduce the effects of within-site variability (Curran [in press, 1987a]; Hawkes 1986). Due to circumstances beyond CFS control, this new study concentrates primarily on data for the upper-elevation plots. New fire impact monitoring plots were established near two of these (Fig. 2).

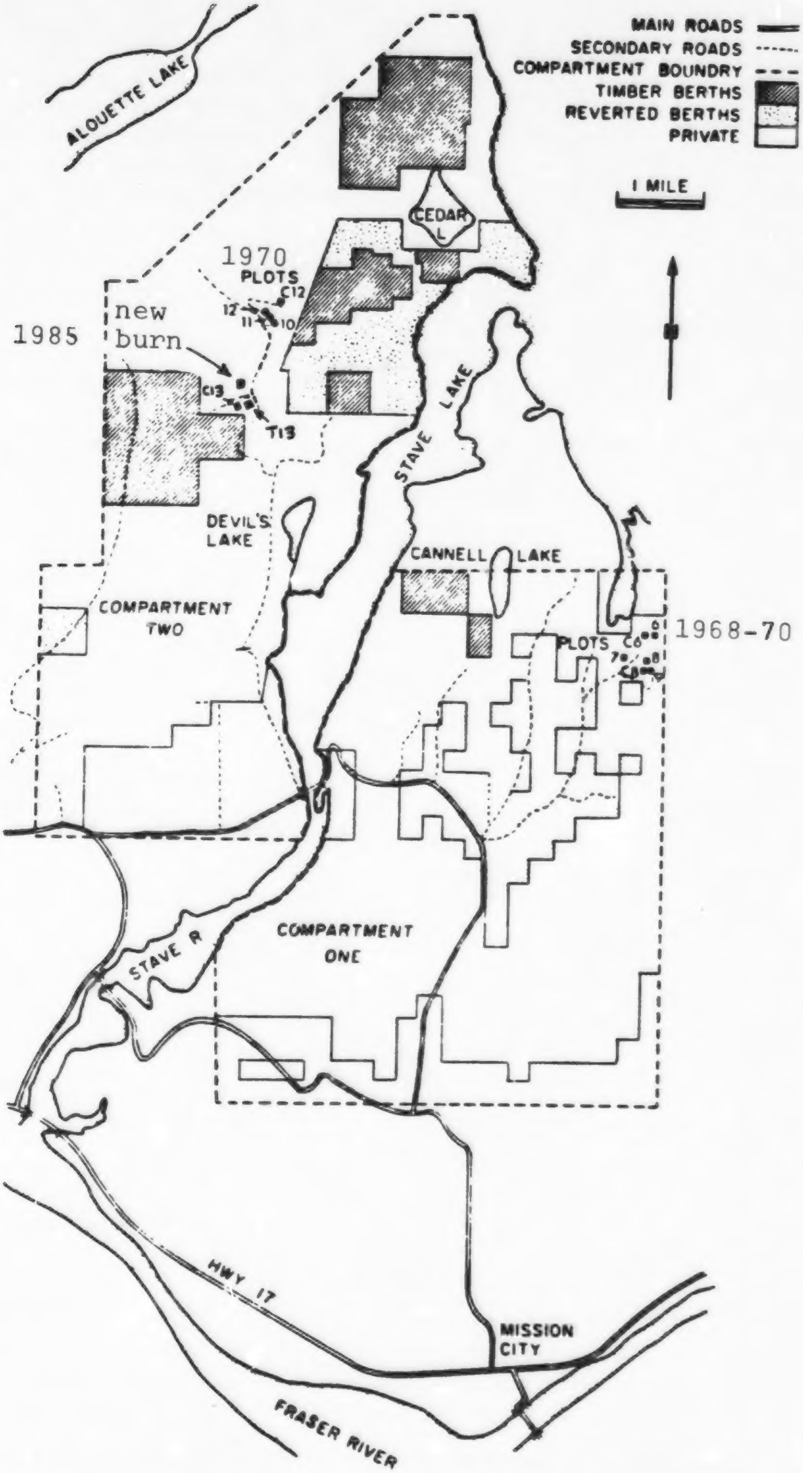
ALOUETTE LAKE
MAIN ROADS
SECONDARY ROADS
COMPARTMENT BOUNDRY
TIMBER BERTHS
REVERTED BERTHS
PRIVATE
1 MILE
CEDAR L
1970
PLOTS
C12
12
11
10
1985
new burn
C13
T13
STAVE LAKE
DEVIL'S LAKE
CANNELL LAKE
COMPARTMENT TWO
PLOTS C6
7
C8
1968-70
COMPARTMENT ONE
STAVE R
HWY 17
MISSION CITY
FRASER RIVER

FIGURE 1. Map of Mission Tree Farm showing location of CFS fire research plots from 1968 to 1970 (from Lafferty 1972).

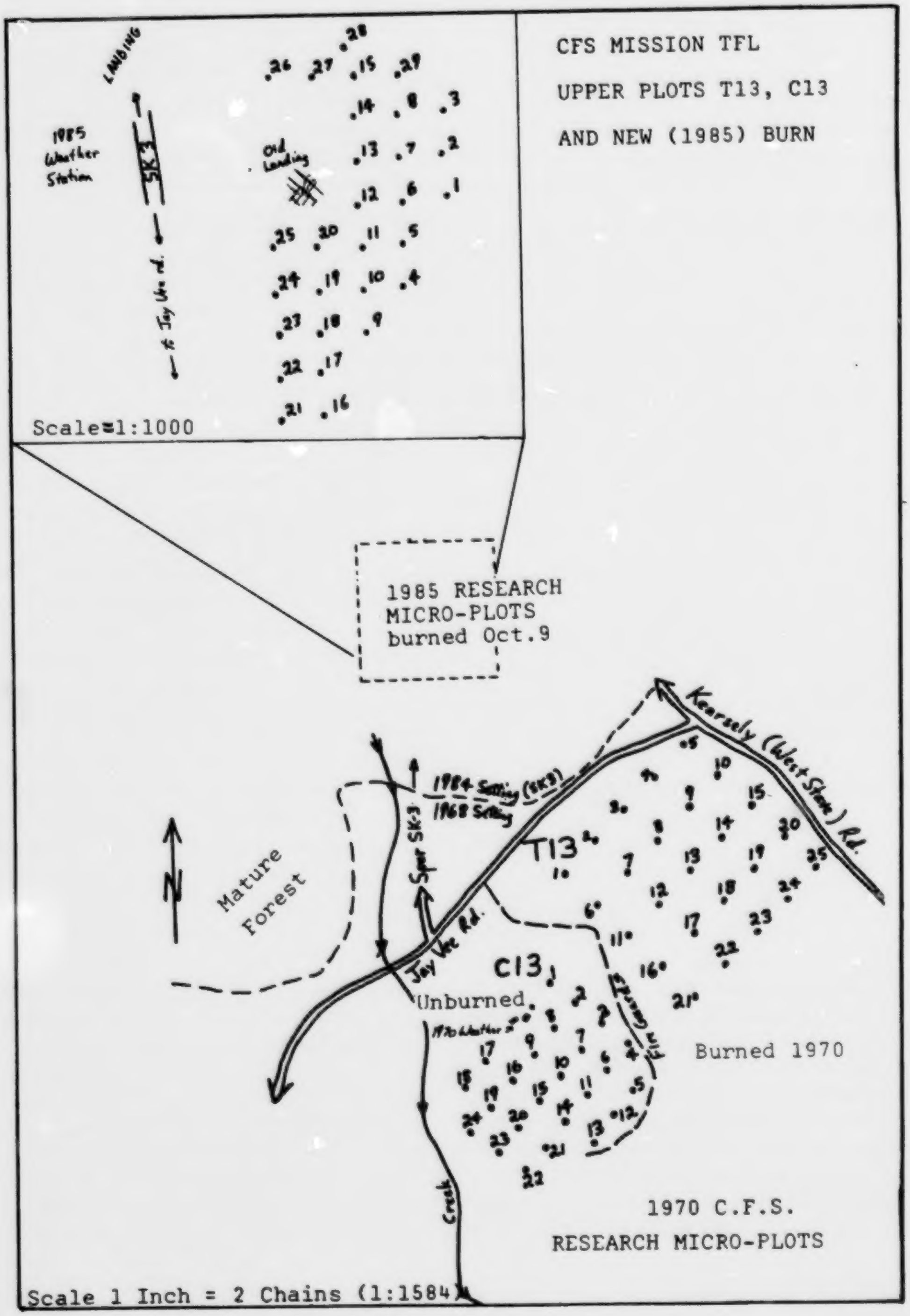
CFS MISSION TFL
UPPER PLOTS T13, C13
AND NEW (1985) BURN
LANDING
1985 Weather Station
SK3
to Joy Vee rd.
Old Landing
Scale=1:1000
1985 RESEARCH
MICRO-PLOTS
burned Oct.9
N
Mature Forest
1984 Setting (SK3)
1968 Setting
Spur SK-3
Kearsely (West Stave) Rd.
T13
Joy Vee Rd.
C13
Unburned
1970 Weather St.
Fire Guard
Burned 1970
Creek
1970 C.F.S.
RESEARCH MICRO-PLOTS
Scale 1 Inch = 2 Chains (1:1584)

FIGURE 2. Map showing location of the 1985 slashburning micro-plots and the adjacent 1970 CFS micro-plots at Mission Tree Farm.

3 METHODS AND MATERIALS

The original CFS plots were relocated using detailed plot plans and permanent markings in the field. Foliar sampling, soil sampling, sample preparation, and laboratory analyses follow the guidelines of Ballard and Carter (1986). Soil analysis for available P and extractable cations (K, Ca,Mg, Mn, Zn, Fe, and Cu) follow the Mehlich 3 extractant (Mehlich 1984). Appropriate soil testing procedures are being developed as concurrent research (Curran *et al.* 1986a).

To monitor fire impact from the new slashburn, 29 micro-plots were randomly located on an 8-m grid (random start/orientation) following the methods and rationale of Trowbridge *et al.* (1986) and Hawkes (in press), with modifications for soil sampling. The micro-plots were 3-m triangular fuel transects similar to the 2-m plots used in related CFS research (Hawkes [in press]), with fine fuels sampled along the first 0.75 m of each leg and at eight duff reduction pins (Fig. 3). Soils were sampled pre-burn, within the first week post-burn, after one month post-burn, and in summer 1986. Soil sampling (forest floor, 0-15 cm and 15-30 cm mineral soil) was at four locations per micro-plot, near the midsection of each leg and the plot center, with 20 micro-plots providing the full complement of mineral soil samples. Because of stumps and boulders on the other micro-plots, the successive soil sampling has been limited to these 20 micro-plots.

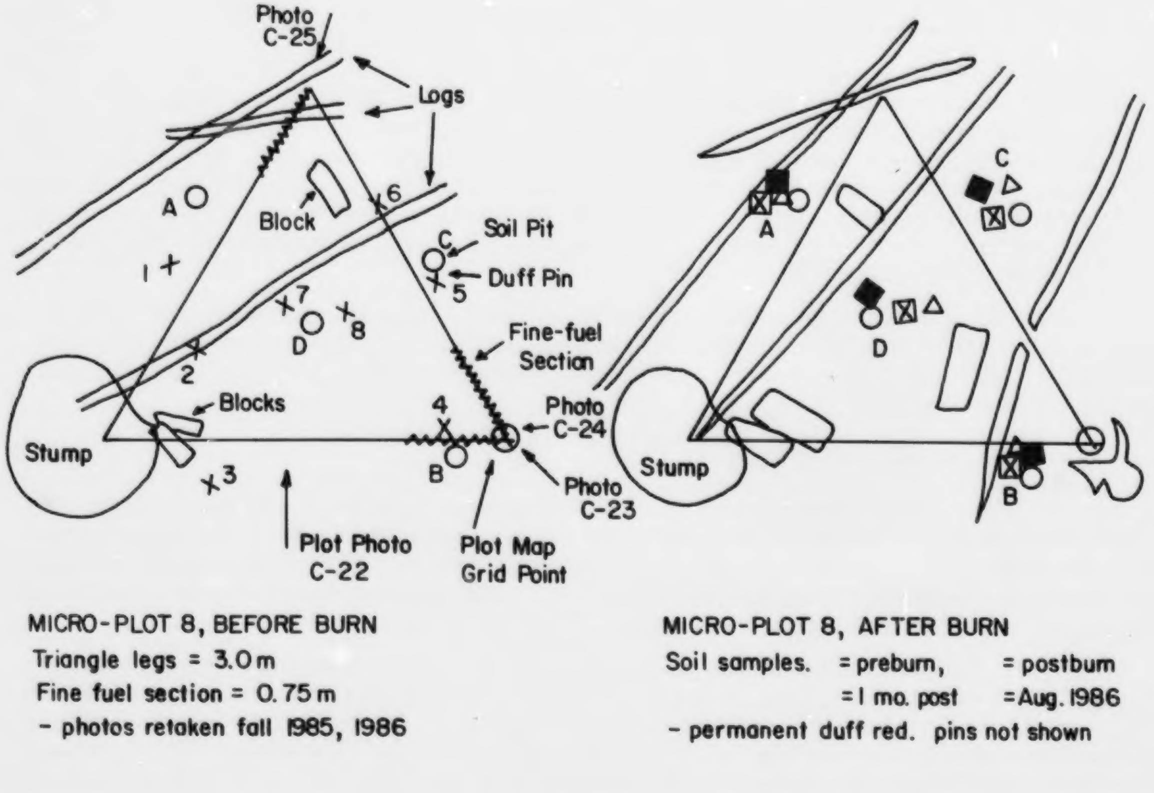
Photo C-25
Logs
A
1
Block
6
Soil Pit
C
Duff Pin
5
7
8
D
2
Fine-fuel Section
Blocks
4
Stump
3
B
Photo C-24
Photo C-23
Plot Photo C-22
Plot Map Grid Point
MICRO-PLOT 8, BEFORE BURN
Triangle legs = 3.0 m
Fine fuel section = 0.75 m
- photos retaken fall 1985, 1986
C
A
D
Stump
B
MICRO-PLOT 8, AFTER BURN
Soil samples. = preburn, = postburn
= 1 mo. post = Aug. 1986
- permanent duff red. pins not shown

FIGURE 3. Plan for new fire research micro-plot 8, burned Oct. 9, 1985.

Two-year-old bareroot Douglas-fir seedlings (Seedlot 1279) were obtained courtesy of the B.C. Ministry of Forests and Lands, and planted on the new burn research micro-plots in spring 1986 (four per plot). Additional seedlings have been planted for comparison of growth in adjacent burned and unburned areas. Some seedlings may be destructively sampled during the early stages of long-term study of fire effects (e.g., for tree growth and nutrient analysis, and for mycorrhizal study).

Mycorrhizal associations are being studied on seedlings grown with inoculum (forest floor and mineral soil from the sites) in growth chambers on the University of British Columbia campus. A factorial experiment is being undertaken, with a random design involving seven treatments (new burn, pre-burn; new burn, immediate post-burn; new burn, one month post-burn; T13 (15-year-old burn); C13 (15-year-old control); mature timber; and unburned portions of the new burn) and two species (Douglas-fir and western hemlock). The experiment is replicated with up to 10 soil samples per treatment at each site and four seedling tubes per soil sample. The work also involves a companion experiment that includes western redcedar and uses soils from some Vancouver Island burns (to provide a wider range of soil properties and time-since-burning). The trees were grown for seven months before they were harvested for analysis. Root system ectomycorrhizae are being evaluated by the methods of Schoenberger and Perry (1982). Endomycorrhizae (i.e., on western redcedar) have been evaluated with the assistance of Dr. S.M. Berch (Dept. of Soil Science, Univ. of British Columbia). Seedlings planted on the research sites in spring 1986 have been evaluated for mycorrhizal inoculation to complement similar studies by other researchers in British Columbia (e.g., at MacMillan Bloedel Ltd.).

Data analysis will be based on normality and equality of variance tests, with correlation and regression analyses planned to provide the data analysis within treatment plots (micro-plot data) and analyses of variance and range tests for evaluation among treatment plots.

4 PRELIMINARY RESULTS AND DISCUSSION

The results to date are preliminary and briefly summarized in this paper, with some detail provided for Douglas-fir growth and nutrition on some high elevation plots. Although a number of relationships have been found between tree growth/nutrition and the detailed fire data, considerably more work is still in progress and detailed discussion at this time would be premature. This on-going work includes: extensive further sampling carried out on the high-elevation plots in fall 1985 to test for confirmation of relationships observed and to verify the original fire data; and analysis of the existing and new data. Therefore, the results summarized here are subject to change, and are not presented statistically.

Relationships between tree growth/nutrition and the detailed fire data suggest differences exist between plots. While these differences have to be statistically verified, it is not wholly certain yet whether they represent treatment effects or simply between-plot variability. These preliminary results are useful in that they support the additional studies undertaken.

4.1 Tree Growth and Nutritional Status

Amabilis fir growth was best on the control plots (C12, C13) and appeared to drop off with increasing burn intensity. Western redcedar growth was also best on plot C12, but no trend was apparent with fire intensity on a plot-by-plot basis. Consideration of the silvics of these species and the results of the on-going nutritional analysis may partly explain the trends observed. There are sufficient western redcedar samples to permit data analysis to determine the existence of possible relationships with the micro-plot fire data.

Douglas-fir growth was best overall on low-elevation plot T6 (Table 2); however, height increment data suggest that growth rate is decreasing. Growth on T7 and T8 currently suggests that heights on these plots could eventually be similar to heights on T6 (although volume trends may be different). Douglas-fir on all three low-elevation plots have low foliar Mg, Fe, and Zn, low foliar N on T7 and T8, low foliar P on T6 (perhaps accounting partly for the growth decline), and low foliar K on the shallow soil stratum of T7. Western hemlock growth and nutrition on plots T7 and T8 are below potential (Table 2), suggesting multiple nutrient deficiencies (low foliar N, P, Fe, Zn, Cu). Without control plots or detailed treatment plot maps for locating fire data points, it cannot be determined if fire has aggravated or induced (or even improved) the growth and nutritional status observed on the low-elevation plots; however, the data will provide an opportunity to test the application of detailed findings from the high-elevation plots.

For the high-elevation plots, growth of Douglas-fir was greatest on T12 (with T11 similar) and poorest on C12 (colder microclimate probable). Western hemlock has grown best on C13, with C12 heights greater than T11 or T12. For both Douglas-fir and western hemlock, growth on T11 and T12 is generally weakly correlated with nutrient levels expressed on a concentration basis. (Analysis of Douglas-fir data on a content basis is in progress). On these plots, Douglas-fir is low in foliar Mg, western hemlock is low in foliar Zn and possibly N, and both species are low in foliar P and Fe. Data for western hemlock on control plot C12 suggest that burning has not affected nutrition (Douglas-fir data analysis for C12 is still in progress).

TABLE 2. Summary of 1984 growth data for Douglas-fir and western hemlock on CFS fire research plots

DOUGLAS-FIR GROWTH DATA FOR SAMPLED PLOTS
(height and length data are averages, in m)

Plot	Fire Intensity	Year(s) Planted	n	Total Height	Leader Length	Inter-node 1	Inter-node 2
T6	High	Fall, 1969 Spr., 1970	15	14.4670	0.8467	0.9533	1.0667
T7	Mod.	Fall, 1968 Spr., 1969	20	9.4225	0.8225	0.7675	0.7500
T8	High	Fall, 1969 Spr., 1970	15	9.9133	0.9467	0.9467	0.9133
T11	Mod.	Fall, 1970	16	8.9719	0.9156	0.8531	0.8094
C12	N/A	Fall, 1970	4	6.5000	0.8375	0.8750	0.6750
T12	Low	Fall, 1970	16	9.1687	1.0062	0.9188	0.7875
C13	N/A	Fall, 1970	29	8.207	1.055	1.009	0.9283
T13	Mod.	Spr., 1971	76	8.5117	0.9125	0.8625	0.8342

WESTERN HEMLOCK GROWTH DATA FOR SAMPLED PLOTS
(height and length data are averages, in m)

Plot	Fire Intensity	Year(s) Burned	n	Total Height	Leader Length	Inter-node 1	Inter-node 2
T7	Mod.	Sept. 9, 1968	13	5.9308	0.6692	0.6462	0.5346
T8	High	Sept. 9, 1969	1	4.5000	0.7000	0.7500	0.6500
T11	Mod.	Aug. 26, 1970	13	5.3000	0.5654	0.5385	0.4115
C12	N/A	(Unburned)	6	6.5000	0.5667	0.6667	0.5167
T12	Low	July 9, 1970	15	5.5333	0.6600	0.5300	0.4567
C13	N/A	(Unburned)	34	7.7485	0.800	0.6439	0.6500
T13	Mod.	Sept. 1, 1970	16	6.6000	0.7844	0.6313	0.6219

On plot T13, Douglas-fir growth is greater than on C13, but recent growth increments have been greater on C13 suggesting a possible growth cross-over occurring between treatment and control, as was observed in Norway by Bråathe (1974). On T13, Douglas-fir is low in foliar Mg and B, western hemlock is low in foliar P and possibly N, and both species display low foliar K, Fe, and Zn. Data for Douglas-fir on plot T13 and C13 (Tables 3 and 4) indicate that burning has most likely reduced the current availability of K, Fe, B, and Zn; similar results are expected upon completion of the western hemlock analysis. Preliminary results from the initial sampling suggest that growth of both species on T13 is correlated with some foliar nutrient levels, with fewer correlations suggested for western hemlock, possibly because of the relatively drier site conditions.

4.2 Relationships of Tree Growth and Nutrition to Fire Data

The upper-elevation micro-plots have been relocated (e.g., Figs. 4-8). Relationships with the CFS fire data appear to exist for both species on plot T11, with total height and some foliar nutrients correlated with a number of fire variables. Douglas-fir foliar P, K, Mn, and Zn concentrations appear related to T11 fire data. Similar relationships are suggested for western hemlock foliar N, Ca, Fe, and Cu. In contrast, growth of both species on plot T12 appears to be unrelated to fire data, but N, P, and Zn levels appear to be related (as well as Mg and B for western hemlock, and Cu for Douglas-fir).

TABLE 3. Douglas-fir foliar nutrient analysis for treatment plot T13

SPECIES : *Pseudotsuga menziesii* — Coastal Douglas-fir
SAMPLE : 84CD T13 — STAND AGE : 16 years

LOCATION: latitude: 49°17' longitude: 122°22' elevation: 620 metres
MISSION TREE FARM - PRESCRIBED FIRE PLOT T-13

BGCL SYNTAXON: CWHb1 — RELATIVE HYGROTOPE: 1 - 4
ABSOLUTE TROPHOTOPE CLASS: nutrient - B - D
PLANT ASSOCIATION: *Tsuga, Pseudotsuga, Thuja, (Abies), Rubus spect., Pte*

Diagnosis is based on analysis of 61 trees.
Burned Sept. 1, 1970; Relative Burn Intensity: Moderate
Planted spring 1970

ELEMENT or RATIO	CURRENT YEAR		COMMENTS
	% or PPM	% DEV / ADEQUATE	
Macronutrient status (%) :			
N	1.434	6	Adequate
P	0.204	36	Adequate
K	0.495	-24	Slight to moderate deficiency
Ca	0.281	12	Adequate
Mg	0.090	-18	Slight to moderate deficiency
Element concentration ratios :			
N/P	7.029		No P deficiency; NID is unlikely
P/A1	6.581		(No interpretation)
K/Ca	1.762		(No interpretation)
Ca/Mg	3.122		(No interpretation)
Sulfur analysis (%) :			
S	0.165	3	No S deficiency; NID unlikely
N/S	8.712		No S deficiency; NID unlikely
Micronutrient status (ppm) :			
Fe	32.400	-28	Possible or near-deficiency
Mn	339.000	1256	No deficiency
Zn	10.000	-17	Possibly moderate deficiency
Cu	4.900	88	No deficiency
B	8.980	-25	Deficiency likely

Supply of nutrients in ranked order: Fe ≤ B ≤ K ≤ Mg ≤ Zn ≤ S ≤ N ≤ Ca ≤ P ≤ Cu ≤ Mn

TABLE 4. Douglas-fir foliar nutrient analysis for control plot C13

SPECIES : *Pseudotsuga menziesii*
SAMPLE : 84CD C13

Coastal Douglas-fir
STAND AGE : 16 years

LOCATION: latitude: 49°17' longitude: 122°22' elevation: 620 metres
MISSION TREE FARM - PRESCRIBED FIRE PLOT C-13

BGCL SYNTAXON: CWHb1
ABSOLUTE TROPHOTOPE CLASS: nutrient - B - D
PLANT ASSOCIATION: *Tsuga, Pseudotsuga, Abies, Rubus spect., Vacci*

RELATIVE HYGROTOPE: 4 - 6

Diagnosis is based on analysis of 29 trees.
Unburned Control Plot
Planted fall 1970

ELEMENT or RATIO	CURRENT YEAR		COMMENTS
	% or PPM	% DEV / ADEQUATE	
Macronutrient status (%) :			
N	1.468	9	Adequate
P	0.202	35	Adequate
K	0.630	-3	Little if any deficiency
Ca	0.273	9	Adequate
Mg	0.090	-18	Slight to moderate deficiency
Element concentration ratios :			
N/P	7.267		No P deficiency; NID is unlikely
P/A1	5.050		(No interpretation)
K/Ca	2.308		(No interpretation)
Ca/Mg	3.033		(No interpretation)
Sulfur analysis (%) :			
S	0.159	0	S deficiency and NID are unlikely
N/S	9.210		No S deficiency; NID unlikely
Micronutrient status (ppm) :			
Fe	39.100	-13	Possible or near-deficiency
Mn	381.000	1424	No deficiency
Zn	12.000	-0	Slight possibility of deficiency
Cu	4.600	77	No deficiency
B	9.670	-19	B possibly deficient; possible NID

Supply of nutrients in ranked order: B ≤ Mg ≤ Fe ≤ K ≤ S ≤ Zn ≤ N ≤ Ca ≤ P ≤ Cu ≤ Mn

On plot T13, in contrast to the apparent effect of burning on nutrition and growth being related to some of these nutrients, Douglas-fir growth generally correlates poorly with fire data, while western hemlock growth correlates well. Micro-plot relationships of fire data with nutritional status support the suggestion that fire has affected nutrient levels (they are usually negative). The B, K, and Zn relationships that might exist on this plot suggest leaching and/or atmospheric losses attributable to burning 14 years before sampling.

4.3 Soil Analyses

Soil analyses for mineralizable N, pH, total N, and organic matter suggest that a number of the current soil properties have been affected by vegetational differences that have occurred on C13 and T13 since burning (Mechlin 1985). However, some weak positive relationships appear to exist between fire data and mineralizable N and soil pH. M.J. Douglas' preliminary mineralizable N results for Vedder Mountain and the new burn (Curren *et al.* 1986a) suggest that on some sites there is at least a short-term reduction in mineralizable N attributable to burning.

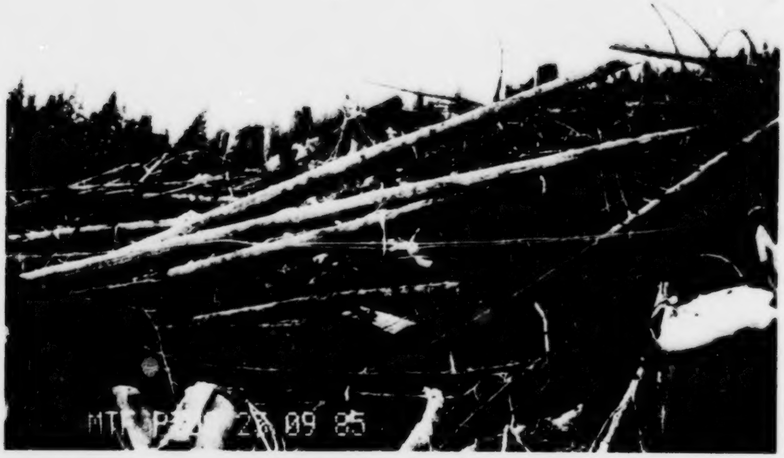

FIGURE 4. CFS micro-plot No. 13 on T13 before burning (Mr. Ogilvie pictured).

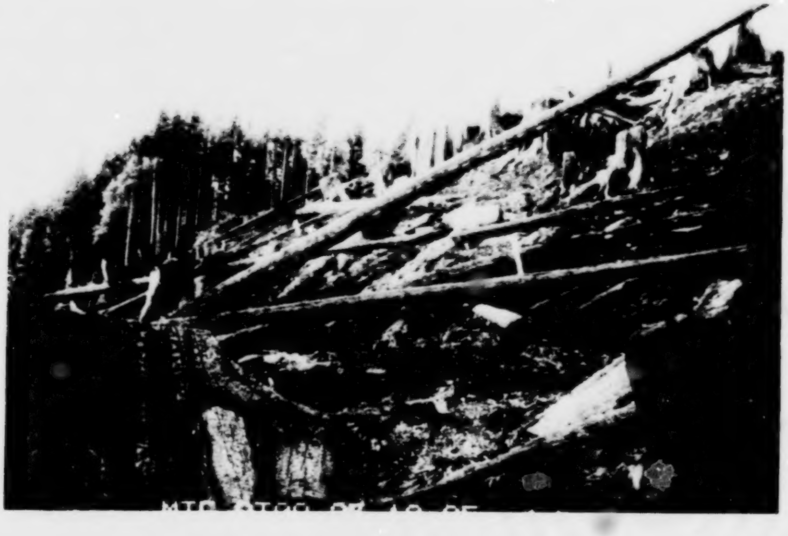

FIGURE 5. CFS micro-plot No. 13 on T13 after burning.

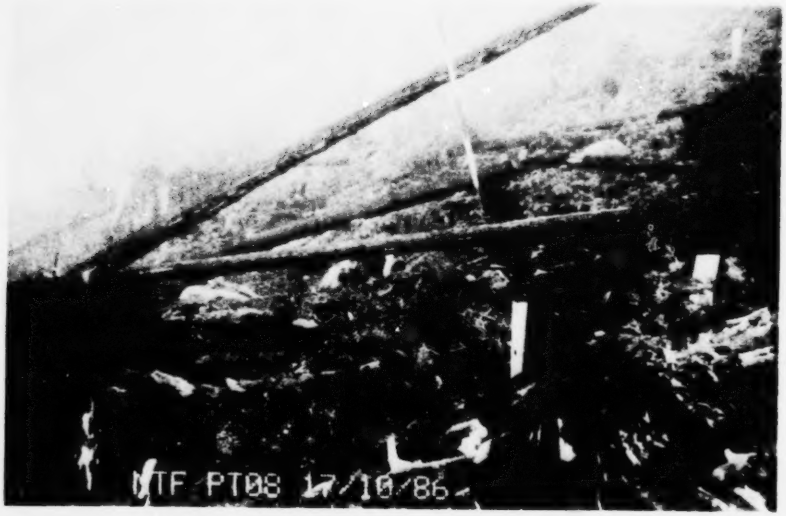
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FIGURE 6. CFS micro-plot No. 13 on T13 during first summer.

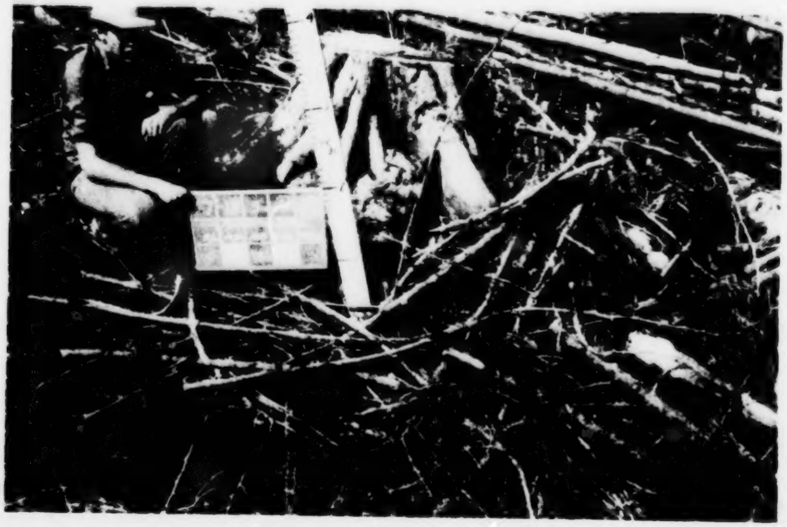

FIGURE 7. CFS micro-plot No. 13 on T13 during second summer.

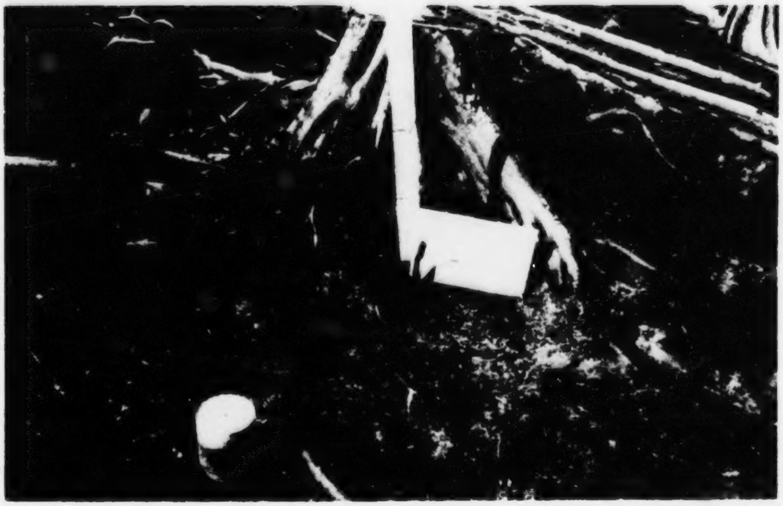

FIGURE 8. CFS micro-plot No. 13 on T13 (general vicinity), fall 1984.

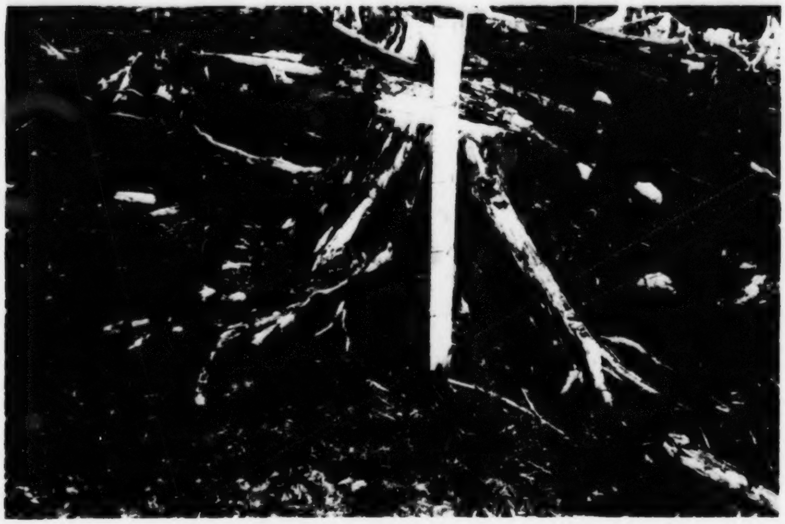

FIGURE 9. New burn micro-plot No. 8 before burning.

4.4 New Fire Impact Plots

The new slashburn was carried out on October 9, 1985; out of an average initial slashloading of 185 tonnes/ha, 104 were consumed, and average duff reduction was 2.8 cm, from a pre-burn average of 14.7 cm. Average impact on individual micro-plots ranged from 17 to 348 tonnes/ha slash consumption, and 1.4 to 4.8 cm duff reduction (average of eight pins). This represents a moderate range of impact (e.g., Figs. 9-11) and, as suggested by Hawkes (in press), it appears that a moderate impact burn will provide an adequate range for regression analysis of burning effects among the micro-plots.

4.5 Growth Chamber Study of Fire Effects on Mycorrhizal Associations

Preliminary analysis of the western redcedar results suggests that mycorrhizal associations in this species may be encouraged by low-impact slashburns, but are discouraged by high-impact burns. The soils for the western redcedar study came from a re-burned slashburning plot from MacMillan Bloedel research on Vancouver Island. The low-impact spring burn had an average duff reduction of 2.4-12.5 cm remaining, with the very high-impact fall re-burn consuming virtually all of this (Beese 1986). Twenty-five cedar trees grown in with pre-burn soil samples had an average colonization level of 11.2%, with this increasing to 27.5% for 31 post low-impact, and dropping to 3.8% for 37 post high-impact trees. The unbalanced design reflects the availability of soil samples. None of 10 growth-chamber control trees had any mycorrhizal colonization. Further data analysis is in progress (the data here are the result of adding all trees, colonized and not, for a gross average), and the data for Douglas-fir and western hemlock are coming available.

PRELIMINARY CONCLUSIONS AND RECOMMENDATIONS

Considerable work is still in progress and the results summarized here are preliminary. These results are of scientific interest because they enable the following conclusions and recommendations. (Further data analysis will address more operational concerns such as stocking level).

Treatment plot maps and micro-plots, which enabled sampling for quantitative analysis of large paired data sets (fire and growth/nutrition data), have facilitated the discovery of apparent relationships between tree growth/nutrition and fire impact data. Results for Douglas-fir and western hemlock demonstrate the dramatic increase in sensitivity and the importance of site-specific information provided by the paired tree-site impact sampling, possible on micro-plots similar to those at Mission Tree Farm (Curran and Ballard 1986; Curran 1988; Hawkes [in press]). Future sampling on these and/or similar plots should consider sampling the perimeter of the plots (adjacent fire data points) to produce large, evenly represented data pairings for analysis.

Tree growth and nutrition results varied with species and with plot,suggesting that it is advisable to look at a range of sites, stands, and times since treatment. Recent preliminary results from related research on CFS micro-plots at Pacific Rim National Park (Curran and Ballard 1986) and CFS plots at Carnation Creek Experimental Watershed and the 47-year-old treatment plots of Mr. Tom Wright (Wright 1942;[1] Curran *et al.* 1986b) suggest similar relationships may exist elsewhere — and attest to the usefulness of the micro-plot approach.

In summary, the following points can be made at this time:

1) Micro-plots used in the original fire monitoring have proved invaluable in initial attempts to define relationships between tree performance and site impact within individual treatment areas;
2) Variation in results from the various treatment plots suggest that it is necessary to look at a range of site, stand, fire, and age conditions. Related research (Curran and Ballard 1986; Curran *et al.* 1986b) is addressing this concern;

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[1] Wright, T.G. 1942. Fieldbook from permanent plots established in Franklin River area on Vancouver Island. MacMillan Bloedel Limited and University of British Columbia.

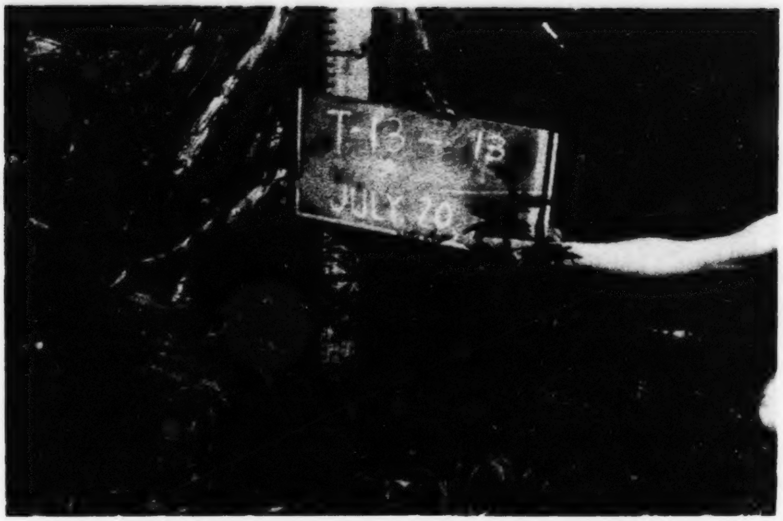
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FIGURE 10. New burn micro-plot No. 8 after burning.

FIGURE 11. New burn micro-plot No. 8 during the next summer.

3) Relationships discussed are under further evaluation, but suggest that some fire impact data may be better than others for long-term study. This is supported by Curran and Ballard (1986) who found that large fuel consumption appeared to be consistently correlated with tree growth and nutrition on some plots at Pacific Rim National Park;

4) Confounding factors, such as vegetation, may prevent resolution of some long-term trends, such as for mineralizable N. However, we are collecting a large data set that will permit the evaluation of long-term effects on competing/indicating vegetation;

5) Mineralizable N appears to be negatively affected by slashburning in the short term (e.g., perhaps at least one year); and

6) Permanent marking of micro-plots has facilitated the study of past research sites, which themselves can yield valuable feedback for current forest management activities and current research addressing mitigation and prevention of reforestation backlog.

6 ACKNOWLEDGEMENTS

The project was initiated in 1984 under funding from MacMillan Bloedel Limited and the B.C. Science Council. Major funding for this project has been provided by contracts and grants to Dr. T.M. Ballard from the B.C. Ministry of Forests (1984-85) and the Canadian Forestry Service (1985-87). The Municipality of Mission was responsible for the new slashburn. A number of personnel at all these agencies have been and continue to be important to the success of the final products. M.J. Douglas assisted with most of the soil sampling, and C.P. Price, E. Wollterson, and R. Lowe assisted with most of the field and laboratory work.

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AN ASSESSMENT OF LANDING REHABILITATION ACTIVITIES IN THE PRINCE GEORGE EAST FOREST DISTRICT

W.W. Carr[1] AND A.J. McLeod[2]

ABSTRACT

Landing rehabilitation guidelines have recently been adopted by the Prince George Forest Region. One purpose of these guidelines is to restore commercial forest production on these severely degraded sites. Three major landing rehabilitation projects were undertaken by the Prince George East District in 1984. Evaluation of the effectiveness of these projects in meeting guideline objectives was initiated in 1985. For a short-term approach to evaluating the effectiveness of rehabilitation, a comparison of selected measurable soil properties from "rehabilitated" and adjacent cut-over areas served as a surrogate for forest productivity. The enhancement of soil nutrient levels and physical parameters to (or toward) acceptable minimum levels for commercial tree growth is used to define successful rehabilitation. Results pertaining to soil physical properties and nutrient status are presented.

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A PRACTICAL FOREST RESOURCES PLANNING SYSTEM

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The following is a brief description of an effective, practical planning system developed by Silva Ecosystem Consultants Ltd. This system can be applied to the planning of all forested areas and to a broad range of forest management objectives. For objectives such as wildlife or fisheries habitat and recreational activities, supplemental data specific to these land uses will be needed. An important premise of the system is that forest planning is carried out (1) to identify areas that have land uses more important than timber and/or are too sensitive to withstand timber harvest, and (2) as to design timber operations in forests.

A complete, practical forest inventory that stratifies the forest into forest ecosystem types and maps their location is the basis of the system. Sampling and plan development are carried out by watershed units. This results in plans that recognize the potential "downstream" impacts of forest management activities.

Flexibility permits application of the planning technique to collect specific data or a broad comprehensive data base. Regardless of the data details or planning resolution desired, the system employs the same approach to data collection. This feature results in practical data collection to meet present objectives and provides for cost-effective data upgrading to meet future needs. Since data upgrading is cost effective, the planning system is an efficient means to obtain data confidence levels necessary to plan and operate effectively on politically and environmentally sensitive sites.

1 LEVELS OF PLANNING

Three levels of planning, from broad planning for large areas to detailed planning for specific areas, are employed. Field procedures and data collection are identical for each planning level; the only variation is the intensity of sampling. Thus, data can be efficiently upgraded to improved levels of resolution by the researcher/planner moving to a more detailed planning level. Data collected along transects will vary with land uses under consideration. To facilitate upgrading, transects used to collect field data are permanently marked in the field at the valley and management unit planning levels. To select the appropriate forest land use(s), to have efficient forest management operations, and to avoid site degradation, planning must occur in the following sequence:

1.1 Valley Planning

- considers all potential forest land uses
- selects major land use(s)
- identifies initial management units comprising similar large terrain units, ecosystem types, terrain stability, wildlife and fish habitats, and water courses (rivers, lakes, streams)
- locates main roads to serve all of valley area for those land uses requiring road access (resolution 1:15 000 - 1:20 000)

1.2 Management Unit Planning

- selects forest land use or mixture of uses suited to specific units
- finalizes management units
- where timber extraction is a designated land use:
  - identifies initial harvest unit (block) boundaries
  - locates secondary roads within individual management units
  - prescribes general silvicultural and logging systems (resolution 1:5000 - 1:10 000)

1.3 Operations Unit Planning

- where timber extraction is the specified land use:
  - locates remainder of haul roads, landings, skidroads, and other components of logging system
  - finalizes block boundaries
  - finalizes silvicultural and logging systems (resolution 1:1000 - 1:3000)

2 DATA COLLECTION AND INTERPRETATION

2.1 Map and Air Photo Study

The largest scale topographic maps and air photos are studied to define the area to be assessed and to provide:

- a general familiarity with the terrain
- an initial stratification of the area by ecosystem and terrain types
- an estimate of the potential of the area for various forest land uses

2.2 Establishment of Transects

Data are collected and survey control established along marked transects, which are located approximately perpendicular to the elevational contours. Adjacent transects will not necessarily be parallel. Distance between transects varies, decreasing with:

- more intense levels of planning
- greater complexity of terrain ecosystems
- decreased visibility within the forest
- planning objectives

Guides to transect separation are:

Valley planning - 300 - 500 m
Management unit planning - 150 - 350 m
Operations unit planning - 100 - 200 m
Note: Valley and management unit intensity transects are permanently marked in the field so that both may be used in the location of operations unit transects.

Data collected along transects include:

a. Survey and terrain data
   - slope distance
   - slope percent
   - azimuth
   - location of existing features such as roads, old skidroads, seismic lines, cabins, etc.
   - location of terrain features such as slope breaks, benches, permanent water courses, intermittent water courses, poorly drained areas, rock outcrops, exposed bedrock, etc.
   - obstacles to harvest operations such as windfall, boulders, etc.
   - important features including wildlife and fish habitat, unique ecosystems, domestic water supplies, residential capabilities, recreation potential

   Field notes comprising standard survey information are kept along with a detailed map of the transect route at a scale of approximately 1:1000. The map accurately shows topographic features, along with any other pertinent data, and forms a key part of the planning process.

b. Site characteristics data

Site characteristics are used to make land use decisions, to design implementation of land uses chosen, and to establish standards for land uses. The three levels of this planning system permit land uses, design, and standards to be "fine tuned" as planning resolution increases. Where timber harvesting is a specified land use, site characteristics are used to calculate the terrain unit stability, to determine stand volumes, to calculate growth and yield rates, and to determine the appropriate silvicultural system and harvest technique for the site. The site characteristics form the basis for decisions and include:

- terrain unit stability factors
  - terrain
  - uniformity/complexity
  - slope gradient
  - frequency of slope breaks
  - recent historic evidence of slope failures
- site moisture regime as related to hygrotope and drainage
- indicator vegetation
- soil
  - depth of LFH
  - texture
  - soil pH
  - gradation
  - depth to impermeable layer
  - mottles/gleying/free water
- stand characteristics, sampled by height classes, includes natural regeneration
  - species
  - density
  - height
  - diameter at breast height
  - age
  - rings last 2 cm of diameter
  - % live crown
  - crown width
  - health and vigour rating - subjective rating based upon foliage colour, length, density and whether buds are filled and turgid
  - indicators of disease, insects, and physiological problems
- stand characteristics, not sampled by height class
  - % crown closure
  - dominance pattern

These variables are recorded on a site characteristics card each time one or more change significantly, or at minimum frequency of 200 m along a transect. The recording of site characteristics is not a "plot" approach but a sample point representing a critical microsite, or a general area (± 2 ha). Both fixed radius plots and/or variable radius plot sampling may be employed in sampling site characteristics.

2.3 Map Production

Following the completion of data collection for a particular planning level, the transect terrain data and significant site characteristic changes are plotted at an appropriate scale. The map scale varies with the intensity of data collection, with the following as a guide:

Valley level	1:10 000 - 1:20 000
Management unit level	1: 5000 - 1:10 000
Operations unit level	1: 1000 - 1: 3000

Maps at each planning level form the base data for decisions required at that planning level. At the valley level and management unit level, practical overlay map systems are often incorporated. The overlay maps may be based upon an expanded transect data base (compared to B.2 above) and/or on data from other sources.

2.4 Summarizing of Site Characteristics

The map and the site characteristics data are used to stratify the area into ecosystem/terrain units. Similar ecosystem/terrain units may have similar management objectives and may be managed with similar methods. In valley plans, this stratification forms the basis of selecting the most desirable land use or mixture of land uses and of the initial management units. In management unit plans, site characteristics summaries finalize the management units and identify the initial management operations units. In an operations plan, the stratification forms the basis for the selection of appropriate operations techniques and standards. Where timber harvesting is the designated land use, site characteristic strata are used to select silvicultural and logging systems.

2.5 Rating of Terrain Unit Stability

Terrain unit stability is a rating used to predict potential site degradation if construction activities (roads, logging, mining, trails) are carried out on the site. Ratings of "moderately stable" and "unstable" may prevent certain activities. For example, timber harvesting would be excluded on sites with unstable ratings. Ground skidding would only be permitted on stable and certain moderately stable sites. Yarding or aerial logging systems should be required on most moderately stable sites and those unstable sites considered possible to log without excessive levels of site degradation and without significant negative effects to associated ecosystems.

The site characteristics described in 2.2.b above form the basis for the rating. Through the application of terrain unit stability ratings, site degradation from soil disturbance and damage to water courses can be minimized. As with any ecological rating system, however, its use and accuracy depend on the ability and objectivity of the user.

2.6 Pre-harvest Planning

Where timber harvesting is a designated land use, the following interpretations occur:

a. The terrain unit stability and site characteristics are used to determine the silvicultural system, including:
   - trees to be felled, trees to leave
   - method of regeneration, species selection, stock type(s), planting density, time of planting
   - logging system (cable yarding, ground skidding, etc.)
   - harvest moisture conditions (season of harvest)
   - operations unit boundaries
   - maximum acceptable soil disturbance
   - site preparation prescriptions
   - potential rehabilitation plans
   - pre-commercial or commercial thinning prescriptions

b. Map layout
   The initial location of transportation, silvicultural and logging system components is determined on the map as appropriate to the level of planning being performed.

c. Field layout
   Using the map layout as a guide, the transportation, silvicultural and logging systems components are laid out in the field. From valley to operations level, the order in which the major components are laid out is:
   - main roads
   - secondary roads

- spur roads
- landings
- others applicable to the specific logging system (skidroads, tailhold cat roads, yarding routes, etc.)
- block boundaries

All components are traversed and plotted on the operations level map. Summaries of silvicultural and logging prescriptions are contained on the operations map. This map forms the primary means of communication between all parties involved in a timber harvesting operation.

d. Operations phase
Following field layout of the transportation, silvicultural, and logging systems, the unit is ready for harvest. Familiarity with all portions of the harvest operation by machine operators and other workers, along with continuous monitoring by competent supervisors, provides the best chance for success. People who performed the planning are usually the best choice to carry out supervision of operations. Planning must be ongoing during operations. Adjustments are made where necessary to maintain efficiency and to meet the operations standards.

e. Evaluation phase
Evaluation is a part of supervision and is ongoing throughout the operations phase. Post-harvest evaluation is performed to:
- rate the success of obtaining minimal soil disturbance during a harvest operation. The level of soil disturbance is assessed and compared with the pre-harvest operation standards.
- provide a basis for planning future operations through learning by experience.
- develop rehabilitation plans as required

Evaluation is performed on the operations level map and includes the establishment of representative transects that locate and measure soil disturbance. The map is adjusted to show any modifications from the planned system, and an overall rating of the operation (satisfactory, marginal, unsatisfactory) is determined.

SOIL COMPACTION AND BIOLOGICAL ACTIVITY: A BRIEF REVIEW

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ABSTRACT

Compaction reduces gas diffusion in soil by decreasing total pore space, especially of larger pores, thus reducing the effective diffusion coefficient. Research has shown gas diffusion to cease at about 10% air-filled porosity (air-filled pore volume/total soil volume). This alteration in soil aeration influences microbial and root activity. Aerobic microbial activity decreases with less than about 25% air-filled porosity. In terms of oxygen concentrations, some microbial activity continues even when gas phase concentrations are as low as 2% oxygen. Tree roots seem more sensitive to decreased soil aeration, and root growth decreases dramatically at 10% oxygen concentration. Although it would appear that roots might be more adversely affected by changes in soil aeration, neither air-filled porosity nor gas phase oxygen concentration alone are sufficient to describe the effect of compaction on soil aeration. Interactions among roots, micro-organisms, and gas diffusion properties must all be considered and need to be studied for a better understanding of the system as a whole. Modeling may be a useful tool in approaching this problem.

1 EFFECTS OF COMPACTION ON PHYSICAL PROPERTIES

Compaction directly affects several physical soil properties. Bulk density increases due to a decrease in macroporosity. Compaction also results in the conversion of macropores to micropores, which alters aeration, infiltration, and hydraulic conductivity (Greacen and Sands 1980). Soil strength also increases. Although these changes in soil physical properties have direct and indirect impacts on seedling survival and growth, the mechanisms through which these impacts occur are not well understood.

It has been shown that growth limiting bulk densities occur and vary with soil texture. Daddow and Warrington (1983) developed an empirical relationship that correlated growth-limiting bulk densities with average pore radius. By determining percent sand, silt, and clay and calculating average pore radii, a limiting bulk density can be found. High silt or clay soils had growth-limiting bulk densities ranging from 1.45 to 1.40 Mg m^{-3}, while values for sandy soils were as high as 1.65-1.75 Mg m^{-3} (Daddow and Warrington 1983). Before a soil reaches this point of severe compaction, seedlings already show significant growth reduction. Bulk densities of this magnitude may reflect a limiting soil strength which cannot be penetrated by roots. Before such limiting values are encountered, other factors likely play a significant role in reducing tree growth (Froehlich and McNabb 1984).

Taylor (1949) found that gas diffusion rates decreased with increasing bulk density and water content. When relative diffusivity (the diffusion rate in a given medium relative to the diffusion rate in air) was plotted against air-filled porosity, a positive linear relationship was observed. Others (Grable and Siemer 1968; Lai *et al.* 1976) have found that curvilinear representations better describe this relationship. Upon further investigation, Currie (1983) found that this relationship consisted of two parts. At lower air-filled porosities, the relationship was curvilinear and represented diffusion through aggregates, while at higher air-filled porosities, diffusion occurred through macropores between aggregates and was more linear in nature. Currie (1984) found that compaction affected gas diffusion as a function of air-filled porosity. The effect was different than when moisture content alone was varied, and was suggested to be the result of two factors. First, compaction changed crumb structure so that as the soil was dried, the observed increase in diffusion was not as great as that for non-compacted soil. Thus the first pores to empty were no longer as efficient at transporting gases because of the distortion from the compaction. Second, an increase in the bulk density reflected increased amounts of crumbs. Therefore intra-crumb pore space increased, resulting in lower diffusion rates. Simply wetting a sample did not reflect the permanent increase in intra-crumb diffusion, although some changes were noted with wetting and drying.

When samples are compared at the same water potential, compacted soils will have higher volumetric water content (Grable and Siemer 1968; Reicosky *et al.* 1981) and lower diffusion rates (Currie 1984; Pritchard 1985). The greatest changes in diffusion rates per unit change in water content were seen at the point when inter-aggregate pore space was drained and water was held only within the intra-aggregate space, i.e., about field capacity. These results illustrate the dependency of soil aeration on both total porosity and pore size distribution, with gas diffusion effectively halted when total air-filled porosity drops below about 10% in soils (Cannell 1977).

2 EFFECTS OF SOIL COMPACTION ON BIOLOGICAL ACTIVITY

2.1 Microbial Activity

It should be noted that very few studies have directly examined the effect of soil compaction on microbial activity. However, the most likely effect is on gas transport in soils. Reduced aeration and lower gas diffusion as a result of compaction could have various biological impacts, depending on whether microbes or tree roots are first affected. If microbes are more sensitive to lower aeration, reduced nutrient mineralization or losses from denitrification may result in fertility problems.

Fungal populations are sensitive to soil structure and thus affected by soil compaction. A study of compaction on forest soils found significant differences in fungal populations between control and compacted plots (Smeltzer *et al.* 1986). Total fungal populations were lower on the compacted plots. Interestingly, *Fusarium* spp., which are often pathogenic to young plants, reacted in the opposite manner. These differences were significant for at least two years following compaction, but after five years differences could no longer be detected. This same study found no significant differences in total bacterial populations as a result of compaction at any time during the study period.

Measurements of total microbial populations may be indicative of overall status of a system. However, activity measurements are a more direct measure of the impact of a given perturbation to the system. For example, Dick[1] found that soil enzymes were more sensitive than total microbial biomass to soil compaction, although both measurements were significantly lower in compacted soil. Soil respiration rates are also lower in compacted soil (F. Pascoe and D. Myrold, Oregon State Univ., unpublished data), at least under laboratory conditions. Most other relevant studies have examined the effect of aeration on biological activity in compacted soils, using two different measures of aeration: oxygen concentration of the gas phase, or some measure of air-filled porosity.

Parr and Reuszer (1962) studied the effect of oxygen concentration on organic matter decomposition. They found that CO_2 evolution at 5% oxygen was about half that at atmospheric oxygen concentrations, however, decomposition at 0.5% oxygen was still almost three times the anaerobic rate. The work of Greenwood (1961) also illustrates the ability of aerobic heterotrophs to metabolize actively at low oxygen concentrations. He found that K_m values for oxygen uptake (the oxygen concentration at which oxygen uptake is half the maximum rate) were approximately 4 M, which corresponds to about 0.3% oxygen in the gas phase. Similarly, Greenwood (1962) found little change in nitrate and nitrite concentrations at oxygen concentrations as low as 2%, suggesting that autotrophic nitrifiers were not inhibited at this oxygen concentration.

Linn and Doran (1984) worked on tilled and nontilled soils, with bulk densities of 1.4 and 1.14 Mg m^{-3}, respectively. They found that aerobic microbial activity increased until the water-filled pore space reached 60% (water volume/total pore volume), which corresponds to 25% air-filled porosity (air-filled pore volume/total soil volume). At this point of maximum aerobic activity, anaerobic processes were still negligible. Aerobic processes decreased and anaerobic processes increased at higher levels of water-filled pore space, indicating that oxygen diffusion was becoming limiting. Although the data of Linn and Doran suggested that 25% air-filled pore space was optimal for aerobic microbial activity in soils, other data suggest that this optimum value may be soil dependent. For example, Bridge and Rixon (1976) found maximum oxygen uptake rates varied between 15 and 30% air-filled porosity for soils of three different textures. Jawson and Skopp (1985) have shown that a maximum in microbial activity can be predicted with a model that links soil diffusion and soil microbial processes using water content or air-filled porosity as the input variable.

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[1] Dick, R.P., Dept. of Soil Science, Oregon State University, Corvallis, pers. comm.

Smith and Cook (1946) found significant differences in nitrate production between compacted (air-filled porosities of 7.1% and lower) and non-compacted treatments. Similar results were obtained by Whisler *et al.* (1965), who looked at aeration effects on microbial activity and found a highly significant correlation between air-filled porosity and nitrate production for two of the three soils. These were soils with low (6.7% and lower) air-filled porosity. Oxygen diffusion at this low level of air-filled porosity probably represents a limiting value for nitrification in these soils. Nitrogen fixation rates in soil have also been shown to be affected by compaction. Landina and Klevenskaya (1985) observed lower rates in compacted soils (bulk densities of 1.3-1.4 Mg m^{-3}, 7-16% air-filled porosities) than in noncompacted soils (1.1-1.2 Mg m^{-3}, 10-19% air-filled porosities).

These data illustrate the effect of oxygen concentration or air-filled porosity on aerobic microbial activity. Generally, optimum aerobic activity occurs at about 25% air-filled porosity and aerobic activity becomes greatly depressed at less than 10% air-filled porosity. Alternatively, aerobic activity decreases at oxygen concentrations less than about 2-5%. However, neither oxygen concentration nor air-filled porosity alone completely describes the supply of oxygen to micro-organisms in soil.

2.2 Root Growth

Soil aeration effects on plant root growth were examined by Leyton and Rousseau (1958). They found that oxygen concentration less than 6-10% greatly reduced root growth expressed as a percentage of growth under normal aeration conditions. A compilation of data from 11 studies for various plant crop species showed critical oxygen concentrations for roots to be around 10-15% (Glinski and Stepniewski 1985). Greenwood (1971), reviewing aeration and its effect on plant growth, noted that root elongation was decreased to 70% of maximum with oxygen concentrations of 6%, although some studies had shown little effect at oxygen concentrations as low as 2%.

Fewer studies on the effect of compaction on root growth have used porosity changes as an index. Foil and Ralston (1967) found inversely proportional linear relationships between bulk density and root length or root weights. They also presented data for non-capillary pore space (air-filled porosity at -6 kPa) that suggested that root growth was decreased approximately 50% when non-capillary pore space was less than about 10%.

Skinner and Bowen (1974) found strong trends showing that compaction reduced mycorrhizal strand penetration by 73% in unsterilized forest soil. However, they found increased mycorrhizal penetration in the compacted soils that had been sterilized. This could suggest that microbial activity, in concert with poorer gas transport of the compacted soil, further decreased oxygen concentration, thereby reducing mycorrhizal growth.

Although both root growth and microbial activity exhibit a wide variation in responses, the data do seem to indicate a higher sensitivity to oxygen deficit for roots, perhaps because of the higher respiration rates of roots compared to that of bulk soil (Glinski and Stepniewski 1985). Aeration and gas diffusion affect both microbial activity and root activity, but there is also an interaction between the two. Conceivably, under given conditions of air-filled porosity, soil conditions could be aerobic or anaerobic depending on the activity of the roots and microbes. Modeling gas diffusion is one way to examine this interaction.

3 MODELING SOIL COMPACTION EFFECTS ON BIOLOGICAL ACTIVITY

Numerous models of oxygen diffusion and consumption in soil systems exist, with varying levels of complexity. These models can be divided into four general categories: (1) gas diffusion in a homogeneous soil profile (Radford and Greenwood 1970; Kanwar 1986), (2) gas diffusion within soil aggregates (Currie 1961; Greenwood 1961), (3) gas diffusion in aggregated soils (Smith 1980), and (4) root aeration models (Armstrong and Beckett 1985).

For example, when the data of Currie (1984) are substituted into a steady state model of gas diffusion in a homogeneous soil profile described by Glinski and Stepniewski (1985), the depth of aerobic soil conditions is calculated to decrease by a factor of three as soil was compacted from a bulk density of 0.99-1.29 Mg m^{-3}. Using a representative soil respiration rate of $7.3x10^{-7}$ cm^3 0_2 cm^{-3} s^{-1}, this translates into the depth of aerobic soil changing from 1 to 0.35 m in compacted soil at field capacity. Results such as these illustrate the importance of interactions between soil physical and biological processes.

Of course, real soils are composed of soil aggregates, which greatly modify the soil microenvironment and consequently affect soil biological activity. The measurement of oxygen profiles within soil aggregates and the influence of these gradients on denitrification are just one example (Sexstone *et al.* 1985). Data such as these could be used to verify models of intra-aggregate diffusion. The implications of such models would be the prediction of microsites within the soil where different activities could occur.

A more complete model would need to account for diffusion through the inter-aggregate spaces as well as the intra-aggregate spaces (cf. Smith 1980). Unfortunately, this type of model has not yet been tested against experimental data. In addition, models of root growth, respiration, and distribution must be incorporated into soil gas diffusion models so that the entire plant soil system can be adequately described.

4 CONCLUSION: RESEARCH NEEDS

It is clear that soil compaction affects aeration and gas diffusion and that this effect is more complicated than a simple decrease in total porespace. Despite this complexity, our understanding of the physics of this phenomenon is reasonably good, at least compared to our knowledge of the effects of compaction-related aeration on microbial activity and plant growth. Research is needed on both plant roots and microbes, and, perhaps most importantly, on interactions between the soil physical system, microbial activity, and plants. Measurements of the effect of soil compaction on plants and the resultant changes in soil aeration must examine more than just root growth. Since shoot-to-root ratios, for example, may vary in response to compaction, simple root growth measures may be inadequate. Work of this type is necessary if we are to increase our understanding of how soil compaction degrades site quality.

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CLOSING REMARKS

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How does one summarize and close a workshop that started with a flourish in the first session and that maintained momentum, interest and challenge throughout? Let me begin by attending to some "housekeeping chores." On behalf of the Research Branch and the rest of the Ministry, I would like to express a large vote of thanks and appreciation to:

- Gerry Still and the other members of the organizing committee;
- all the speakers and poster-presenters, especially those here on their own time, for their excellent presentations, their motivation and their attitudes;
- all the session chairmen for keeping us on time and coordinating the individual sessions;
- the question runners; - those who provided the logistical support with registration, visual aids equipment, coffee and doughnuts; and
- lastly, the audience for your participation, your motivation and your patience; the success of the workshop is indicated by the number of audience members here right to the end.

All those listed above have contributed to a workshop that provided not only an occasion to discuss a timely and important aspect of soil science and forest management, but also an opportunity for good interaction between researchers and operational foresters and engineers. I believe that the proceedings of this workshop will be a much-used and often-cited benchmark publication within the forestry community in British Columbia.

In summary, I feel the major points or questions raised during the workshop are:

1. We have some serious problems related to soil degradation in many areas of the province, and we have incurred some massive costs and losses.

2. We do have access to appropriate planning strategies, and harvesting and management methods and technology to minimize or avoid some of the soil degradation losses that have normally been incurred, and rehabilitation methods and technology to reduce the level of degradation on some severely disturbed sites. Even with these tools in hand, we do not have a good record of implementation in British Columbia.

3. Concern has been raised that we do not understand the nature of our soil resource sufficiently and its behaviour under stress.

4. The nature of soil degradation problems is often difficult to define; we need new approaches and methods/technology to quantify degradation effects accurately.

5. We need adequate and appropriate legislation to regulate activities that cause degradation and we need adequate enforcement capabilities.

6. Rehabilitation of degraded forest soils has not proven to be cost effective, but it is responsible forest land management. The high costs of rehabilitation can be substantially reduced, or even eliminated in some cases, if we attempt to understand the resource we are managing and undertake appropriate planning procedures to avoid or minimize soil degradation in the first place.

7. We must be aware that, while the severe soil degradation problems are easy to identify and describe, there are much more subtle degradation problems associated with silvicultural activities which must be understood and accommodated when we define and implement our management objectives. How well we understand and manage our soils determines the ultimate success of our silviculture plans.

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Many of the presentations have offered us some solutions to these problematic points and questions, and I think these solutions can be grouped into three areas:

1. More information needed: Through research and operational trials, we must generate new and better information to allow us to assess the nature, extent and rehabilitation requirements of soil degradation problems in British Columbia more capably and accurately.
2. More extension and demonstration: Better and greater use can be made of existing information and expertise to ensure more appropriate planning, more careful operations, and more effective rehabilitation plans and activities. Information/technology transfer and demonstration, particularly through effective training, are a top priority in many areas of forest management today in British Columbia.
3. Improved attitudes: We cannot expect to deal effectively with our soil degradation problems if we do not increase the level of respect for our soils resource and for responsible integrated land management objectives. Soil is a major forest resource that is affected directly by forest management and must be recognized as such. While there are still so many uncertainties about the causes, nature and extent of forest soil degradation, it is important to adopt a conservative resource management attitude and assume that unless we know better, loss of productivity as a result of forest soil disturbance is significant. This means that allowances for the same must be made in TSA analyses, and efforts must continue to reduce unnecessary soil disturbance in forest management operations.

Thank you again, one and all!

Appendices

APPENDIX 1. Workshop participants

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